

Solutions Manual to Accompany

Basic Principles and Calculations in Chemical Engineering

Seventh Edition

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TYPICAL EXAMS FOR A ONE SEMESTER COURSE
(scheduled in the evening to avoid time constraints on students)

Exam No. 1
(Open Book, 1 1/2 hours)

PROBLEM 1 (5%)

Hydrogen can be separated from natural gas by diffusion through a round tube. The rate of separation is given by

$$N = 2 \pi D \rho R$$

where

- N = rate of transport of H_2 from the tube, g moles/(sec)(cm of length of tube)
 D = diffusion coefficient
 ρ = molar density of H_2 , g moles/cm³
 R = log mean radius of tube, $r_2 - r_1 / \ln \left(\frac{r_2}{r_1} \right)$, with r in cm.

What are the units of D ?

PROBLEM 2 (10%)

A pallet of boxes weighing 10 tons is dropped from a lift truck from a height of 10 feet. The maximum velocity the pallet attains before hitting the ground is 6 ft/sec. How much kinetic energy does the pallet have in (ft)(lb_f) at this velocity?

PROBLEM 3 (5%)

The specific gravity of a fuel oil is 0.82. What is the density of the oil in lb/ft³? Show all units.

PROBLEM 4 (10%)

Sulfur trioxide (SO_3) can be absorbed in sulfuric acid solution to form more concentrated sulfuric acid. If the gas to be absorbed contains 55% SO_3 , 41% N_2 , 3% SO_2 , and 1% O_2 , how many parts per million of O_2 are there in the gas? (b) What is the composition of the gas on a N_2 free basis?

PROBLEM 5 (15%)

You have 100 kilograms of gas of the following composition:

CH_4	30%
H_2	10%
N_2	60%

What is the average molecular weight of this gas?

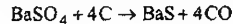
PROBLEM 6 (15%)

If the heat capacity of a substance is 5.32 J/(g)(°C) and its molecular weight is 37.4, what is its heat capacity in

- (a) J/(g)(°F)
(b) J/(lb)(°R)
(c) J/(gmol)(K)

PROBLEM 7 (20%)

A rock containing 100% $BaSO_4$ is burned with coke (94%C, 6% ash) and the composition of the product is $BaSO_4$ (11.1%) BaS (72.9%), C(13.9%, ash (2.2%). The reaction is



Calculate the percent excess reactant, and the degree of completion of the reaction.

PROBLEM 8 (20%)

A gas cylinder to which is attached an Bourden gage appears to be at a pressure of 27.38 in. Hg at 70°F. the barometer reads 101.8 kPa. A student claims that the pressure in the tank is 1.3 psia, but another student points out that this is impossible - the pressure is really 28.2 psia. Can 1.3 psia be correct? Explain and show calculations to back up your explanation.

EXAM NO. 2
(Open Book, 2 hours)

PROBLEM 1 (25%)

A chemist attempts to prepare some very pure crystals of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ by dissolving 200 g of Na_2SO_4 (MolWt=142.05) in 400 g of boiling water. He then carefully cools the solution slowly until some $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ crystallizes out. Calculate the g of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ recovered in the crystals per 100 g of initial solution, if the residual solution after the crystals are removed contains 28% Na_2SO_4 .

Right answer but: -10 if answer is in g of Na_2SO_4 and not g of $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ -10 if answer not per 100 g of initial soln

PROBLEM 2 (25%)

Water pollution in the Hudson River has claimed considerable recent attention, especially pollution from sewage outlets and industrial wastes. To determine accurately how much effluent enters the river is quite difficult because to catch and weigh the material is impossible, weirs are hard to construct, etc. One suggestion which had been offered is to add a trace Br^- ion to a given sewage stream, let it mix well, and sample the sewage stream after it mixes well.

On one test of the proposal you add ten pounds of NaBr per hour for 24 hours to a sewage stream with essentially no Br^- in it. Somewhat downstream of the introduction point a sampling of the sewage stream shows 0.012% NaBr . The sewage density is 60.3 lb/ft^3 and river water density is 62.4 lb/ft^3 .

What is the flow rate of the sewage in lb/min ?

-10 if answer based on 0.012 fraction and not 0.00012. -15 if 24 hr basis was used and then not converted back to per hour basis.

PROBLEM 3 (25%)

In preparing 5.00 moles of a mixture of three gases (SO_2 , H_2S , and CS_2), gases from three tanks are combined into a fourth tank. The tanks have the following compositions (mole fractions):

Gas	Tank 1	Tank 2	Tank 3	Tank 4
SO_2	0.10	0.20	0.25	0.20
H_2S	0.40	0.20	0.25	0.26
CS_2	0.50	0.60	0.50	0.54

How much of Tanks 1, 2, and 3 must be mixed to give a product with composition of Tank 4?

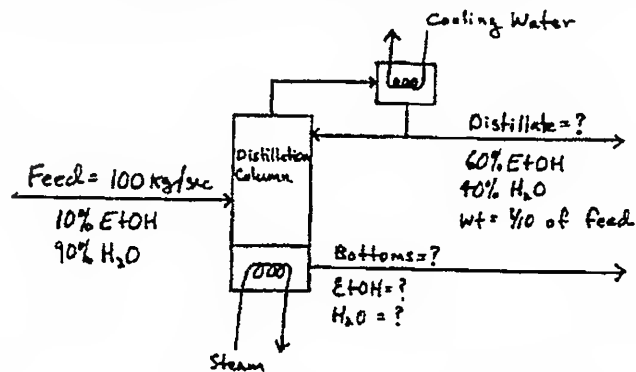
-10 for correct answer but wrong basis

-15 A lot of people said no soln. They used wrong basis, etc. No soln but correct mat'l balance

(continued)

PROBLEM 4 (25%)

- 10% a) For the given distillation process, calculate the composition of the bottoms stream.
- 15% b) If steam leaked into the column at 1000 mole/sec and all else was constant, what would the new bottoms composition be?
 -5 (should be g-mole). if assumed to k-mole and not stated.



Exam No. 3
 (Open Book Exam, 2 hours)

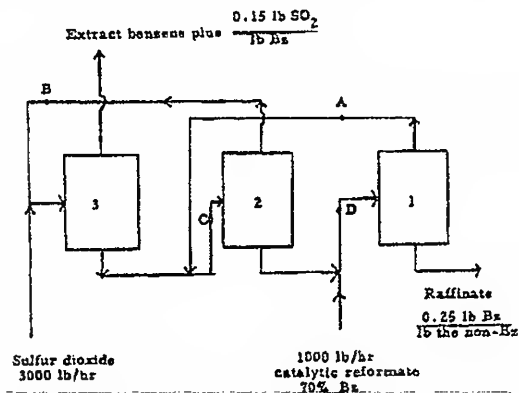
PROBLEM 1 (35%)

A company burns an intermediate product gas having the composition 4.3% CO₂, 27% CO, 10% H₂, 1.0% CH₄, and the residual N₂ together with a waste oil having the composition 87% C, 13% H₂. Analysis of the stack gas gives an Orsat analysis of 14.6% CO₂, 0.76% CO, and 7.65% O₂ and the rest N₂. Calculate the fraction of the total carbon burned that comes from the product gas.

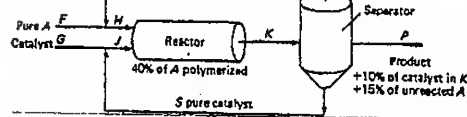
PROBLEM 2 (35%)

Benzene, toluene and other aromatic compounds can be recovered by solvent extraction with sulfur dioxide. As an example, a catalytic reformate stream containing 70% by weight benzene and 30% non-benzene material is passed through the counter-current extractive recovery scheme shown in the diagram below. One thousand pounds of the reformate stream and 3000 pounds of sulfur dioxide are fed to the system per hour. The benzene product stream (the extract) contains 0.15 pound of sulfur dioxide per pound of benzene. The raffinate stream contains all the initially charged non-benzene material as well as 0.25 pound of benzene per pound of the non-benzene material. The remaining component in the raffinate stream is the sulfur dioxide.

- (a) How many pounds of benzene are extracted per hour, i.e. are in the extract?
- (b) If 800 pounds of benzene containing in addition 0.25 pound of the non-benzene material per pound of benzene are flowing per hour at point A and 700 pounds of benzene containing 0.07 pound of the non-benzene material per pound of benzene are flowing at point B, how many pounds (exclusive of the sulfur dioxide) are flowing at points C and D?



(continued)



Reactant A is polymerized as shown in the figure. It is mixed with fresh catalyst and recycled catalyst. Conversion of A is 40% on one pass through the reactor. Fresh catalyst (G) enters at the rate of 0.40 lb G per lb of A in stream H. The separator removes 90% of the catalyst and recycles it as well as recycling unreacted A. Nevertheless, the product stream P constraints 15% of the unreacted A and 10% of the catalyst exiting in stream K as well as the polymer product. Determine the ratio of stream R to G.

Note: catalyst does not react in the process!

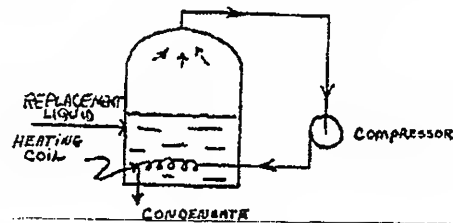
Exam No. 4
(Open Book, 2 hours)

PROBLEM 1 (25%)

In the vapor-recompression evaporator (not insulated) shown in the figure below, the vapors produced on evaporation are compressed to a higher pressure and passed through the heating coil to provide the energy for evaporation. The steam entering the compressor is 98% quality at 10 psia, the steam leaving the compressor is at 50 psia and 400°F, and 6 Btu of heat are lost from the compressor per pound of steam throughput. The condensate leaving the heating coil is at 50 psia, 200°F. The replacement liquid is at the temperature of the liquid inside the evaporator.

Computer:

- the work in Btu needed for compression per pound of H_2O going through the compressor.
- the Btu of heat transferred from the heating coil to the liquid in the evaporator per pound of H_2O through the coil.



PROBLEM 2 (25%)

An insulated, sealed tank that is 2 ft³ in volume holds 8 lb of water at 100°F. A 1/4 hp stirrer mixes the water for 1 hour. What is the fraction vapor at the end of the hour? Assume all the energy from the motor enters the tank.

For this problem you do not have to get a numerical solution. Instead list the following in this order:

- State what the system you select is.
- Specify open or closed.
- Draw a picture.
- Put all the known or calculated data on the picture in the proper place.
- Write down the energy balance (use the symbols in the text) and simplify it as much as possible. List each assumption in so doing.
- Calculate W.
- List the equations with data introduced that you would use to solve the problem.
- Explain step by step how to solve the problem (but do not do so).

PROBLEM 3 (15%)

What is the enthalpy change in Btu when 1 pound mole of air is cooled from 600°F to 100°F at atmospheric pressure.

Compute your answer by two ways:

- Use the tables of the combustion gases
- Use the heat capacity equation for air.

(continued)

PROBLEM 4 (10%)

Answer the following questions by placing T for true and F for false on your answer page. Grading: +2 if correct, 0 if blank, -1 if wrong.

- Heat and thermal energy are synonymous terms used to express one type of energy.
- You can find the enthalpy change at constant pressure of a Substance such as CO_2 from the solid to the gaseous state by integrating

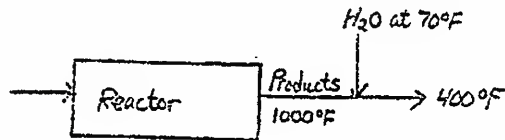
$$\int_{T_1}^{T_2} C_p dT \quad \text{from } T_1 \text{ (solid temperature) to } T_2 \text{ (gas temperature) for a constant pressure path.}$$

- The enthalpy change of a substance can never be negative.
- Heat and work are the only methods of energy transfer in a non-flow process.
- Both Q and ΔH can be classed as state functions (variables)

PROBLEM 5 (25%)

Hot reaction products (assume they have the same properties as air) at 1000°F leave a reactor. In order to prevent further reaction, the process is designed to reduce the temperature of the products to 400°F by immediately spraying liquid water into the gas stream.

How many lb of water at 70°F are required per 100 lb of products leaving at 400°F ?



For this problem you do not have to get a numerical solution. Instead list the following in this order.

- State what the system you select is.
- Specify open or closed.
- Draw a picture.

- Write down the known or calculated data on the picture in the proper places.
- Simplify them as much as possible, list each assumption in so doing.
- Insert the known data into the simplified equation(s) you would use to solve the problem.

Exam No. 5
(Open Book, 2 hours)

PROBLEM 1 (10%)

Answer the following questions briefly (no more than 3 sentences);

- Does the addition of an inert diluent to the reactants entering an exothermic process increase, decrease, or make no change in the heat transfer to or from the process?
- If the reaction in a process is incomplete, what is the effect on the value of the standard heat of reaction? Does it go up, down, or remain the same?
- How many properties are needed to fix the state of a gas so that all of the other properties can be determined?
- Consider the reaction $\text{H}_2(\text{g}) + \frac{1}{2} \text{O}_2(\text{g}) \rightarrow \text{H}_2\text{O}(\text{g})$. Is the heat of reaction with the reactants entering and the products leaving at 500K higher, lower, or the same as the standard heat of reaction?

PROBLEM 2 (10%)

Explain how you would calculate the adiabatic reaction temperature for Problem 5 below if the outlet temperature is not specified. List each step. (You can cite some of the steps listed in Problem 5 if you list them by number in Problem 5.)

PROBLEM 3 (20%)

A flue gas at 750°F and 1 atm of composition 14.0% CO_2 , 1.0% CO , 6.4% O_2 , and the balance N_2 is the product of combustion with excess air at 750°F and 1 atm that is used to burn coke (C).

(continued)

- What is the volume in ft^3 of the flue gas leaving the furnace per pound of carbon burned?
- What is the volume of air in ft^3 entering the furnace per pound of C burned?

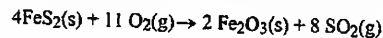
PROBLEM 4 (20%)

Seven pounds of N_2 are stored in a cylinder 0.75 ft^3 volume at 120°F. Calculate the pressure in the cylinder in atmosphere:

- Assuming N_2 to be an ideal gas.
- Assuming N_2 is a real gas and using compressibility factors.

PROBLEM 5 (40%—one half each for the material and energy balances)

Pyrites (FeS_2) is converted to sulfur dioxide (SO_2) gas according to the reaction



The air which is 35% excess (based on the above reaction) for combustion enters at 27°C, the ore at 18°C, and the products leave at 900K. Because of equipment degradation, unburned FeS_2 exits from the process. In one hour 8000 kg of pyrites are fed to the process, and 2000 kg of Fe_2O_3 are produced. What is the heat added or removed from the process? Data: For FeS_2 , $C_p = 44.77 + 5.590 \times 10^{-2}T$ where T is in Kelvin and C_p is in J/(g mol)(K). For Fe_2O_3 , $C_p = 103.4 + 6.71 \times 10^{-2}T$ with the same units.

Exam No. 6
(Open Book, 2 hours)

PROBLEM 1 (20%)

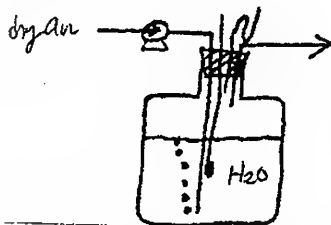
A high pressure line carries natural gas (all methane) at 10,000 kPa and 40°C. How would you calculate the volume of the gas under these conditions that is equivalent to 0.03 m^3 of CH_4 at standard conditions using an equation of state? Select one equation other than van der Waal's equation, and list it on your solution page. Give a list of steps to complete the calculations. Include all the proper equations, and include a list of data involved, but you do not have to obtain a solution for the volume.

PROBLEM 2 (20%)

From the following data estimate the vapor pressure of sulfur dioxide at 100°C.

Temperature (°C)	-10	6.3	32.1	55.5
Vapor pressure (atm)	1	2	5	10

PROBLEM 3 (20%)



Dry atmospheric air at the ambient conditions of 90°F and 29.42 in. Hg absolute passes through a small blower and is bubbled up through water so that the air leaving the water is saturated. The temperature of the water is constant at 80°F, and because of the back pressure in the system, the pressure in the vapor space in the top of the bottle is 2.7 in.

H_2O greater than atmospheric pressure. The bottle is weighted after the air is blown for 2 hours, 13 minutes, 47 seconds, and the decrease in weight was found to be 8.73 lb. What was the hourly rate of flow of air at ambient conditions in ft^3 ?

PROBLEM 4 (20%)

A vessel with a volume of 2.83 m^3 contains a mixture of nitrogen and acetone at 44.0°C and 100.0 kPa. The dew point of the mixture is 20.0°C and the relative saturation of the acetone in the mixture is 58.39%. The vapor pressure of acetone at 44.0°C is 65.35 kPa and it is 24.62 kPa at 20.0°C.

- What is the partial pressure of acetone vapor in the original mixture, in kPa?
- How many kg moles of acetone does the original mixture contain?
- If the nitrogen-acetone mixture is cooled with the volume remaining at 2.83 m^3 constant so that 27.0 percent of the acetone condenses, what is the final temperature of the mixture in °C?

(continued)

PROBLEM 5 (20%)

A wet sludge contains 50 percent water by weight . This sludge is first centrifuged, and 0.1 kilograms of water are removed per kilogram of wet sludge feed. The sludge is dried further using air so that the final product contains 10 percent by weight water. The air for drying is heated, passed into an oven drier, and vented back into the atmosphere. On a day when atmospheric pressure is 760mm Hg, the temperature is 70°F and the relative humidity is 50%, calculate the cubic meters of wet air required to dry one kilogram of sludge fed to the process. The air vented from the oven drier is at 100°F and 780mm Hg. It has a dew point of 94°F.

Solutions Chapter 1

1.1 a. Basis: 1 mi³

$$\frac{1 \text{ mi}^3}{1} \left(\frac{5280 \text{ ft}}{1 \text{ mi}} \right)^3 \left(\frac{12 \text{ in}}{1 \text{ ft}} \right)^3 \left(\frac{2.54 \text{ cm}}{1 \text{ in}} \right)^3 \left(\frac{1 \text{ m}}{100 \text{ cm}} \right)^3 = 4.17 \times 10^9 \text{ m}^3$$

b. Basis: 1 ft³/s

$$\frac{1 \text{ ft}^3}{1 \text{ s}} \left| \frac{60 \text{ s}}{1 \text{ min}} \right| \left| \frac{7.48 \text{ gal}}{1 \text{ ft}^3} \right| = 449 \text{ gal/min}$$

1.2 a.
$$\frac{0.04 \text{ g}}{(\text{min})(\text{m}^3)} \left| \frac{60 \text{ min}}{1 \text{ hr}} \right| \left| \frac{(12 \text{ in})^3}{1 \text{ ft}^3} \right| \left| \frac{1 \text{ lb}_m}{454 \text{ g}} \right| = 9.14 \frac{\text{lb}_m}{(\text{hr})(\text{ft}^3)}$$

b.
$$\frac{2 \text{ L}}{\text{s}} \left| \frac{3600 \text{ s}}{1 \text{ hr}} \right| \left| \frac{24 \text{ hr}}{1 \text{ day}} \right| \left| \frac{1 \text{ ft}^3}{28.32 \text{ L}} \right| = 6.1 \times 10^3 \frac{\text{ft}^3}{\text{day}}$$

c.
$$\frac{6 (\text{in.})(\text{cm}^2)}{(\text{yr})(\text{s})(\text{lb}_m)(\text{ft}^2)} \left| \frac{1 \text{ ft}^2}{(12 \text{ in})^2} \right| \left| \frac{(1 \text{ in})^2}{(2.54 \text{ cm})^2} \right| \left| \frac{1 \text{ yr}}{365 \text{ days}} \right| \left| \frac{1 \text{ day}}{24 \text{ hr}} \right| \left| \frac{1 \text{ hr}}{3600 \text{ s}} \right| \left| \frac{2.2 \text{ lb}_m}{1 \text{ kg}} \right|$$

$$\frac{1 \text{ ft}}{12 \text{ in}} \left| \frac{0.3048 \text{ m}}{1 \text{ ft}} \right| = 1.14 \times 10^{-11} \frac{\text{m}}{(\text{kg})(\text{s}^2)}$$

1.3 The Pascal is a pressure unit, defined as 1N/m² and it is not the same as a mass flux unit. The correct equivalent is 3.9 Mg/(h)(m²). If the "lb" means "lb_m" then the conversion is correct. Since the English short ton is not part of SI, "L/ton" is not, either. Correct is "34 gal/ton (142 L/Mg)."

If the ton is a metric ton, then 129 L/ton is correct.

Solutions Chapter 1

1.4 a. Basis: 60.0 mile/hr

$$\frac{60.0 \text{ mile}}{\text{hr}} \left| \frac{5280 \text{ ft}}{1 \text{ mile}} \right| \left| \frac{1 \text{ hr}}{3600 \text{ sec}} \right| = 88 \frac{\text{ft}}{\text{sec}}$$

b. Basis: 50.0 lb_m/(in)²

$$\frac{50.0 \text{ lb}_m}{(\text{in})^2} \left| \frac{454 \text{ g}}{1 \text{ lb}} \right| \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| \left| \frac{1 (\text{in})^2}{(2.54 \text{ cm})^2} \right| \left| \frac{(100 \text{ cm})^2}{(1 \text{ m})^2} \right| = 3.52 \times 10^4 \frac{\text{kg}}{\text{m}^2}$$

c. Basis: 6.20 cm/(hr)²

$$\frac{6.20 \text{ cm}}{(\text{hr})^2} \left| \frac{1 \text{ m}}{100 \text{ cm}} \right| \left| \frac{10^9 \text{ nm}}{1 \text{ m}} \right| \left| \frac{1 (\text{hr})^2}{(3600 \text{ sec})^2} \right| = 4.79 \frac{\text{nm}}{\text{sec}^2}$$

1.5

- (a) N/mm or nm (nanometer)
- (b) °C/M/S
- (c) 100 kPa
- (d) 2.73.15 K
- (e) 1.50m, 45 kg
- (f) 25°C
- (g) J/s
- (h) 250 N

1.6
$$\frac{20 \text{ hp}}{1} \left| \frac{0.7457 \text{ kW}}{1 \text{ hp}} \right| = 14.91 \text{ kW}$$

No, not enough power even at 100% efficiency; 68 kW = 91.2 hp.

Solutions Chapter 1

1.7

$$\frac{1 \text{ hr}}{525 \text{ mile}} \left| \frac{2200 \text{ gal}}{1 \text{ hr}} \right| \left| \frac{1000 \text{ mile}}{1} \right| = 4190.5 \text{ gal}$$

$$\frac{1 \text{ hr}}{475 \text{ mile}} \left| \frac{2000 \text{ gal}}{1 \text{ hr}} \right| \left| \frac{1000 \text{ mile}}{1} \right| = \frac{4210 \text{ gal}}{(20 \text{ gal})}$$

None: 20 gal more are needed.

1.8 Let t_A be the time for A to paint one house; t_B for B. A does a house in 5 hours, or 1 house/5 hr. B does one house in 3 hours, or 1 house/3 hr.

$$\frac{1 \text{ house}}{5 \text{ hr}} \left| \frac{t_A \text{ hr}}{1} \right| + \frac{1 \text{ house}}{3 \text{ hr}} \left| \frac{t_B \text{ hr}}{1} \right| = 1 \text{ house}$$

Also $t_A = t_B$ so that $\frac{3}{15} t_A + \frac{5}{15} t_A = 1$ or $\frac{8}{15} t_A = 1$

$$t_A = \frac{15}{8} \text{ hr} = t_B = 1.875 \text{ hr} \text{ or } 112.5 \text{ min}$$

- 1.9 (a) mass, because masses are balanced
(b) weight, because the force exerted on the mass pushes a spring

$$1.10 \frac{20.0 \text{ g}}{(\text{m})(\text{s})} \left| \frac{1 \text{ lb}_m}{453.6 \text{ g}} \right| \left| \frac{0.3048 \text{ m}}{1 \text{ ft}} \right| \left| \frac{3600 \text{ s}}{1 \text{ hr}} \right| \left| \frac{1(\text{lb}_f)(\text{s}^2)}{32.174(\text{lb}_m)(\text{ft})} \right| \left| \frac{1(\text{hr})^2}{(3600)^2 \text{ s}^2} \right|$$

$$= 1.16 \times 10^{-7} \frac{(\text{lb}_f)(\text{hr})}{\text{ft}^2}$$

Solutions Chapter 1

1.11

$$\frac{1.0 \text{ Btu}}{(\text{hr})(\text{ft}^2)} \left| \frac{24 \text{ hrs}}{1 \text{ day}} \right| \left| \frac{1 \text{ ft}^2}{(12 \text{ in})^2} \right| \left| \frac{1 \text{ in}^2}{(2.54 \text{ cm})^2} \right| \left| \frac{(100 \text{ cm})^2}{1 \text{ m}^2} \right| \left| \frac{1.8^\circ \text{F}}{1^\circ \text{C}} \right| \left| \frac{2.54 \text{ cm}}{1 \text{ in}} \right|$$

$$\frac{252 \text{ cal}}{1 \text{ Btu}} \left| \frac{12 \text{ in}}{1 \text{ ft}} \right| \left| \frac{4.184 \text{ J}}{1 \text{ cal}} \right| \left| \frac{1 \text{ kJ}}{1000 \text{ J}} \right| = 1.49 \times 10^4 \frac{\text{kJ}}{(\text{day})(\text{m}^2)(^\circ \text{C} / \text{cm})}$$

1.12 Basis: 1 lb H₂O

$$\text{a. } KE = \frac{1}{2} mv^2 = \frac{1}{2} \left| \frac{1 \text{ lb}_m}{32.174(\text{ft})(\text{lb}_m)} \right| \left(\frac{3 \text{ ft}}{\text{s}} \right)^2 = 0.14(\text{ft})(\text{lb}_f)$$

b. Let A = area of the pipe and v = water velocity. The flow rate is

$$q = Av = \left(\frac{\pi D^2}{4} \right) (v)$$

$$= \frac{\pi (2 \text{ in})^2}{4} \left| \frac{(1 \text{ ft})^2}{(12 \text{ in})^2} \right| \left| \frac{3 \text{ ft}}{\text{s}} \right| \left| \frac{60 \text{ s}}{1 \text{ min}} \right| \left| \frac{7.48 \text{ gal}}{1 \text{ ft}^3} \right| = 29.37 \text{ gal/min}$$

1.13 Not really – but people do not usually distinguish between mass and weight.

1.14 The object has a mass of 21.3 kg (within a precision of $\pm .1$ kg). The weight is the force used to support the mass.

Solutions Chapter 1

1.15 In American Engineering System

$$\text{Power} = \text{FV}$$

$$= \frac{800 \text{ lb}_f}{1} \left| \frac{300 \text{ ft}}{\text{min}} \right| = \boxed{2.4 \times 10^5 \frac{(\text{lb}_f)(\text{ft})}{\text{min}}} \text{ or } 7.27 \text{ hp}$$

In SI

$$\begin{aligned} \text{Power} &= \frac{4000 \text{ N}}{1} \left| \frac{1.5 \text{ m}}{\text{s}} \right| \left| \frac{1 (\text{watt})(\text{s})}{1 (\text{N})(\text{m})} \right| \\ &= \boxed{6000 \text{ watts}} \end{aligned}$$

1.16

$$\text{KE} = \frac{1}{2} m v^2$$

$$\begin{aligned} & \frac{1}{2} \left| \frac{2300 \text{ kg}}{1} \right| \left| \frac{1 \text{ lb}_m}{0.454 \text{ kg}} \right| \left| \left(\frac{10.0 \text{ ft}}{\text{s}} \right)^2 \right| \left| \frac{1}{32.2 \frac{\text{lb}_m}{\text{lb}_f} \frac{\text{ft}}{\text{sec}^2}} \right| \left| \frac{1 \text{ Btu}}{778.2 (\text{ft})(\text{lb}_f)} \right| \\ &= \\ &= \boxed{10.11 \text{ Btu}} \end{aligned}$$

Solutions Chapter 1

1.17 Basis: 10 tons at 6 ft/s

$$\text{KE} = \frac{1}{2} m v^2 = \frac{1}{2} \left| \frac{20,000 \text{ lb}_m}{1} \right| \left| \left(\frac{6 \text{ ft}}{\text{s}} \right)^2 \right| \left| \frac{1 (\text{s}^2)(\text{lb}_f)}{32.2 (\text{ft})(\text{lb}_m)} \right| = \boxed{11,200 (\text{ft})(\text{lb}_f)}$$

1.18

$$\eta = \frac{\text{numerator}}{\text{denominator}}$$

$$\text{Numerator} = Y_{x/s} \gamma_b \Delta H_{b/e}^c$$

$$= \left(\frac{\text{mol cell C}}{\text{mole substrate C}} \right) \left(\frac{\text{e}^- \text{ equiv.}}{\text{mol cell C}} \right) \left(\frac{\text{energy}}{\text{mol e}^- \text{ equiv.}} \right)$$

$$= \frac{\text{energy}}{\text{mol substrate C}} \quad (1)$$

$$\text{Denominator} = \Delta H_{\text{cat}}^c$$

$$= \frac{\text{energy}}{\text{mol substrate C}} \quad (2)$$

$$\eta = \frac{(1)}{(2)} = \frac{\text{energy}}{\text{energy}}$$

There is no missing conversion factor
What the author claimed about the units is correct.

Solutions Chapter 1

1.19 $Q = 0.61S \sqrt{(2\Delta p)/\rho}$ assume hole is open to atmosphere

$$\Delta p = \frac{144 \text{ in}^2}{1 \text{ ft}^2} \left[\frac{23 \text{ lb}_f}{\text{in}^2} + \frac{73 \text{ in gas.}}{1 \text{ gas.}} \left| \frac{0.703 \text{ H}_2\text{O}}{1 \text{ gas.}} \right| \frac{1 \text{ ft}}{12 \text{ in}} \left| \frac{14.7 \frac{\text{lb}_f}{\text{in}^2}}{33.91 \text{ ft H}_2\text{O}} \right| \right]$$

$$= 3,579 \text{ lb}_f/\text{ft}^2$$

$$\rho = \frac{0.703 \frac{\text{lb}_f}{\text{ft}^3}}{1 \text{ lb}_f/\text{ft}^3 \text{ H}_2\text{O}} \left| \frac{62.4 \frac{\text{lb}_f \text{H}_2\text{O}}{\text{ft}^3 \text{H}_2\text{O}}}{43.87 \frac{\text{lb}_f}{\text{ft}^3}} \right|$$

$$S = \pi \left(\frac{1}{(4)(12)} \right)^2 = 3.41 \times 10^{-4} \text{ ft}^2$$

$$Q = (3600)(0.61)(3.41 \times 10^{-4}) \sqrt{(2)(3579)g_c / 43.87} = \boxed{54 \frac{\text{ft}^3}{\text{hr}}}$$

1.20 No. $q = 0.6(2\text{m}^2) \left[\frac{(2)}{\text{s}^2} \left| \frac{9.8 \text{ m}}{\text{s}^2} \right| \frac{10^{-3} \text{ m}}{\text{kg}} \left| \frac{50 \times 10^3 (\text{kg})(\text{m})}{(\text{s}^2)(\text{m}^3)} \right| \frac{1}{1 - \left(\frac{2}{5} \right)^2} \right]^{1/2}$

The net units on the right hand side of the equation are

$$\text{m}^2 \left[\frac{\text{m}^3}{\text{s}^4} \right]^{1/2} \neq \frac{\text{m}^3}{\text{s}}$$

Consequently, the formula will not yield 80.8 m/s, presumably in the formula the g should be g_c for use in the AE system.

Solutions Chapter 1

1.21

a₁. A is in g/cm³
a₂. B is in g/(cm³)(°C)
a₃. Since the exponent of e must be dimensionless
C is in atm⁻¹

b₁ $A = \frac{1.096 \text{ g}}{\text{cm}^3} \left| \frac{(30.48)^3 \text{ cm}^3}{\text{ft}^3} \right| \frac{1 \text{ lb}_m}{454 \text{ g}} = \boxed{68.4 \frac{\text{lb}_m}{\text{ft}^3}}$

b₂ $B = \frac{0.00086 \text{ g}}{(\text{cm}^3)(^\circ\text{C})} \left| \frac{(30.48)^3 \text{ cm}^3}{\text{ft}^3} \right| \frac{1 \text{ lbm}}{454 \text{ g}} \frac{1^\circ\text{C}}{1.8^\circ\text{R}} = \boxed{0.0298 \frac{\text{lb}_m}{(\text{ft}^3)(^\circ\text{R})}}$

b₃ $C = \frac{0.000953}{\text{atm}} \left| \frac{1 \text{ atm}}{14.7 \text{ lb}_f/\text{in}^2} \right| = \boxed{0.0000648 \frac{1}{\text{lb}_f/\text{in}^2}}$

Solutions Chapter 1

$$1.22 \quad a. \quad Z = 1 + \rho B + \rho^2 C + \rho^3 D$$

$$B \quad \begin{array}{c} \text{Units} \\ \text{cm}^3 / \text{g mol} \end{array}$$

$$C \quad (\text{cm}^3 / \text{g mol})^2$$

$$D \quad (\text{cm}^3 / \text{g mol})^3$$

$$b. \quad Z = 1 + \rho^* B^* + (\rho^*)^2 C^* + (\rho^*)^3 D^*$$

$$B^* \quad \begin{array}{c} \text{Units} \\ \text{ft}^3 / \text{lb}_m \end{array}$$

$$C^* \quad (\text{ft}^3 / \text{lb}_m)^2$$

$$D^* \quad (\text{ft}^3 / \text{lb}_m)^3$$

If B is the original coefficient, B* is obtained by multiplying B by conversion factors. Let MW be the molecular weight of the compound.

$$B^* \frac{\text{ft}^3}{\text{lb}_m} = B \frac{\text{cm}^3}{\text{g mol}} \left(\frac{1 \text{ ft}}{30.48 \text{ cm}} \right)^3 \left| \frac{1 \text{ g mol}}{\text{MW g}} \right| \left| \frac{454 \text{ g}}{1 \text{ lb}_m} \right| = B \frac{0.016}{\text{MW}}$$

$$C^* \left(\frac{\text{ft}^3}{\text{lb}_m} \right)^2 = C \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2 \left(\frac{1 \text{ ft}}{30.48 \text{ cm}} \right)^6 \left(\frac{1 \text{ g mol}}{\text{MW g}} \right)^2 \left(\frac{454 \text{ g}}{1 \text{ lb}_m} \right)^2 = C \frac{2.57 \times 10^{-4}}{\text{MW}^2}$$

$$D^* \left(\frac{\text{ft}^3}{\text{lb}_m} \right)^3 = D \frac{4.096 \times 10^{-6}}{\text{MW}^3}$$

Solutions Chapter 1

$$1.23 \quad u \left[\frac{\text{m}}{\text{s}} \right] = k[1] \left[\left(\frac{\tau}{\rho} \right)^{1/2} \left(\frac{N}{\text{m}^2} \right)^{1/2} \left(\frac{\text{m}^3}{\text{kg}} \right)^{1/2} \right]$$

To get u in ft/s, substitute for τ and for ρ , and multiply both sides of the equation by 3.281 ft/m (k is dimensionless).

$$\tau \frac{\text{N}}{\text{m}^2} = \frac{r' \text{ lb}_f}{\text{ft}^2} \left(\frac{3.281 \text{ ft}}{1 \text{ m}} \right)^2 \left| \frac{1 \text{ N}}{0.2248 \text{ lb}_f} \right|$$

$$\rho \frac{\text{kg}}{\text{m}^3} = \frac{\rho' \text{ lb}_m}{\text{ft}^3} \left(\frac{3.281 \text{ ft}}{1 \text{ m}} \right)^3 \left| \frac{1 \text{ kg}}{0.454 \text{ lb}_m} \right|$$

$$u' = 2.57 k \left(\frac{\tau'}{\rho'} \right)$$

1.24 The left handside has the units of $(\text{length})^{-1}$ and α/a is dimensionless so that the third answer is correct.

1.25 The inside diameter of the tubing is $6.35 - 290.762 = 4.826 \text{ mm}$

$$\text{The flow area is } \frac{\pi}{4} (4.826)^2 \text{ mm}^2 = \frac{(18.292) \text{ mm}^2}{(100) \text{ mm}^2 / \text{cm}^2} = 0.1829 \text{ cm}^2$$

The velocity of the sample gas is

$$(10) \frac{\text{cm}^3}{\text{s}} \left| \frac{1}{(0.1829) \text{ cm}^2} \right| = 54.67 \frac{\text{cm}}{\text{s}}$$

Solutions Chapter 1

For a travel distance of 125 ft, the time required for the flow is

$$\frac{(125)\text{ft}}{(54.67)\frac{\text{cm}}{\text{s}}} \left| \frac{(30.38)\text{cm}}{\text{ft}} \right| = \boxed{69.69 \text{ seconds}}$$

Including the 5-sec instrument delay, about 75 sec will be required for sampling. A delay time of 75 sec may be acceptable for low leak rates, but faster detection would be desired for dangerous concentrations of toxic gases.

- b) To reduce sampling time:
- 1) Increase the flow rate for same diameter tubing,
 - 2) Decrease the tubing diameter for same flow rate,
 - 3) Reduce the tubing length.

- 1.26 Place units for the symbols in the given equation, and equate the units on the left and right hand sides of the equation by assigning appropriate units to the coefficient 0.943.

$$\begin{array}{ccc} \text{LHS} & & \text{RHS} \\ \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(\Delta^\circ\text{F})^2} & \left[\left(\frac{\text{Btu}}{(\text{hr})(\text{ft})(\Delta^\circ\text{F})} \right)^3 \left(\frac{\text{lb}_m}{\text{ft}^3} \right)^2 \frac{\text{ft}}{(\text{hr})^2} \frac{\text{Btu}}{\text{lb}_m \text{ft}} \left| \frac{(\text{hr})(\text{ft})}{\text{lb}_m} \right| \frac{1}{\Delta^\circ\text{F}} \right]^{1/4} \end{array}$$

The units are the same on the right and left so that 0.943 has no units associated with it.

- 1.27 Introduce the units. The net units are the same on both sides of the equation.

$$(\text{ft})(\text{ft})^{1.5} \left(\frac{\text{ft}}{\text{s}^2} \right)^{1/2} = \frac{\text{ft}^3}{\text{s}}$$

Solutions Chapter 1

- 1.28 Basis: Dvp/ μ

$$1. \quad \frac{2 \text{ in}}{\text{s}} \left| \frac{10 \text{ ft}}{\text{ft}} \right| \frac{62.4 \text{ lb}_m}{\text{ft}^3} \left| \frac{(\text{hr})(\text{ft})}{0.3 \text{ lb}_m} \right| \frac{3600 \text{ s}}{1 \text{ hr}} \left| \frac{1 \text{ ft}}{12 \text{ in}} \right| = \boxed{1.248 \times 10^6}$$

$$2. \quad \frac{20 \text{ ft}}{\text{hr}} \left| \frac{10 \text{ mi}}{\text{mi}} \right| \frac{1 \text{ lb}_m}{\text{ft}^3} \left| \frac{(\text{s})(\text{ft})}{0.14 \times 10^{-4} \text{ lb}_m} \right| \frac{5280 \text{ ft}}{1 \text{ mi}} \left| \frac{1 \text{ hr}}{3600} \right| = \boxed{2.10 \times 10^7}$$

$$3. \quad \frac{1 \text{ ft}}{\text{s}} \left| \frac{1 \text{ m}}{\text{m}} \right| \frac{12.5 \text{ kg}}{\text{m}^3} \left| \frac{1}{2 \times 10^{-6} \text{ cp}} \right| \frac{100 \text{ cp}}{1 \text{ p}} \left| \frac{0.305 \text{ m}}{100 \text{ cm}} \right| \frac{1 \text{ m}}{100 \text{ cm}} \left| \frac{10^3 \text{ g}}{1 \text{ kg}} \right| \frac{30.48 \text{ cm}}{1 \text{ ft}} \\ \times \frac{1 \text{ p}}{1(\text{g})/(\text{cm})(\text{s})} = \boxed{5.81 \times 10^7}$$

$$4. \quad \frac{2 \text{ mm}}{\text{s}} \left| \frac{3 \text{ cm}}{\text{cm}} \right| \frac{25 \text{ lb}_m}{\text{ft}^3} \left| \frac{1}{1 \times 10^{-6} \text{ cp}} \right| \frac{100 \text{ cp}}{1 \text{ p}} \left| \frac{454 \text{ g}}{\text{lb}_m} \right| \frac{1 \text{ cm}}{10 \text{ mm}} \left| \frac{\text{ft}^3}{(30.48)^3 \text{ cm}^3} \right| \\ \times \frac{1 \text{ p}}{1(\text{g})/(\text{cm})(\text{s})} = \boxed{2.38 \times 10^7}$$

$$1.29 \quad \dot{m} \left(\frac{\text{ton}}{\text{hr}} \right) = \frac{Q \text{ gal}}{\text{min}} \left| \frac{0.1337 \text{ ft}^3}{1 \text{ gal}} \right| \frac{\rho \text{ lb}_m}{\text{ft}^3} \left| \frac{1 \text{ ton}}{2000 \text{ lb}_m} \right| \frac{60 \text{ min}}{1 \text{ hr}} \\ = Q \rho \left[(4.011 \times 10^{-3}) \left(\frac{(\text{ft}^3)(\text{ton})(\text{min})}{(\text{gal})(\text{lb}_m)(\text{hr})} \right) \right]$$

- 1.30 Two because any numbers added to the right hand side of the decimal point in 10 are irrelevant.

Solutions Chapter 1

1.31 The sum is 1287.1430. Because 1234 has only 4 significant figures to the left of an implied decimal point, the answer should be 1287 (no decimal point).

1.32 The number of significant figures to the right of the decimal point is 1 (from 210.0m), hence the sum of 215.110 m should be rounded to 215.1 m.

1.33 A calculator gives 569.8269 000, but you should truncate to 4 significant figures, or 569.8 cm³.

1.34 Two significant figures (based on 6.3). Use 4.8×10^3 .

1.35 Step 1: The product 1.3824 is rounded off to 1.4

Step 2: Calculate errors.

For absolute error, the product 1.4 means 1.4 ± 0.05

$$\text{Thus } \frac{0.05}{1.4} \times 100\% = 3.6\% \text{ error}$$

$$\text{Similarly } 3.84 \text{ has } \frac{0.005}{3.84} \times 100\% = 0.13\% \text{ error}$$

$$\text{and } 0.36 \text{ has } \frac{0.005}{0.36} \times 100\% = 1.4\% \text{ error}$$

Total 2.7% error

Solutions Chapter 2

2.1 The first paragraph of the letter is ok. In the second paragraph, the author is wrong. The molecular weight, even in SI, is the ratio of mass to moles (or the mass per a fixed number of molecules) and is not dimensionless.

2.2 Yes

2.3 A mole is a number of molecules. Molecular weight is the mass per mole.

2.4 All of the answers are wrong. A mole is a number of molecules.

- a) It is not a number of molecules in a volume
- b) It is not a weight
- c) It is not a number of molecules in a gram
- d) It is not an atomic weight or sum thereof
- e) It is not a molecular weight

2.5 The statement is partially correct. A mole is a number of entities, not a quantity of material. "Quantity" usually is not considered to be enumerated.

2.6 a) mol⁻¹ means the inverse of the unit "mol,"

b) Yes.

2.7 1. (d) 2. (c)

2.8 $\frac{893.51 \text{ g C}}{1 \text{ g mol C}}$ from adding elemental masses

Solutions Chapter 2

2.9 a. Basis: 120 lb mole NaCl: $\frac{120}{1 \text{ lb mol}} \left| \frac{58.45 \text{ lb}}{\text{lb}} \right| \frac{454 \text{ g}}{\text{lb}} = \boxed{3.18 \times 10^6 \text{ g}}$

b. Basis: 120 gm mole NaCl: $\frac{120}{1 \text{ g mol}} \left| \frac{58.45 \text{ g}}{\text{g}} \right| \frac{1 \text{ lb}}{454 \text{ g}} = \boxed{15.4 \text{ lb}}$

c. Basis: 120 lb NaCl: $\frac{120}{1 \text{ lb}} \left| \frac{454 \text{ g}}{\text{lb}} \right| \frac{1 \text{ g mol}}{58.45 \text{ g}} = \boxed{932 \text{ g mol}}$

d. Basis: 120 gm NaCl: $\frac{120}{1 \text{ g mol}} \left| \frac{1 \text{ lb}}{454 \text{ g}} \right| \frac{1 \text{ lb mol}}{58.45 \text{ lb}} = \boxed{4.52 \times 10^{-3} \text{ lb mol}}$

2.10 (a) MW = 40.08 g/g mol + 12.01 g/mol + 2(16.00) g/gmol
= $\boxed{100.9 \text{ g / g mol CaCO}_3}$

b) $\frac{10 \text{ g CaCO}_3}{100.09 \text{ g CaCO}_3} \left| \frac{1.0 \text{ g mol CaCO}_3}{1 \text{ g}} \right| = \boxed{0.0999 \text{ g mol}}$

c) $\frac{20 \text{ lb CaCO}_3}{100.09 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb}} \right| = \boxed{0.200 \text{ lb mol CaCO}_3}$

d) $\frac{2 \text{ lb mol CaCO}_3}{1 \text{ lb mol CaCO}_3} \left| \frac{100.09 \text{ lb CaCO}_3}{1 \text{ lb}} \right| \frac{454 \text{ g}}{1 \text{ lb}} = \boxed{90,880 \text{ g CaCO}_3}$

Solutions Chapter 2

- 2.11. a) $\frac{4 \text{ g mol MgCl}_2}{(95.23) \text{ g MgCl}_2} = \boxed{380.9 \text{ g}}$
- b) $\frac{2 \text{ lb mol C}_3\text{H}_8}{(44.09) \text{ lb C}_3\text{H}_8} \left| \frac{454 \text{ g C}_3\text{H}_8}{1 \text{ lb C}_3\text{H}_8} \right| = \boxed{4 \times 10^4 \text{ g C}_3\text{H}_8}$
- c) $\frac{16 \text{ g N}_2}{(28.02) \text{ g N}_2} \left| \frac{\text{gmol N}_2}{454 \text{ gmol N}_2} \right| \left| \frac{1 \text{ lb mol N}_2}{1 \text{ lb mol N}_2} \right| = \boxed{1.26 \times 10^{-3} \text{ lb mol N}_2}$
- (d) $\frac{3 \text{ lb C}_2\text{H}_6\text{O}}{(46.07) \text{ lb C}_2\text{H}_6\text{O}} \left| \frac{1 \text{ lb mol C}_2\text{H}_6\text{O}}{1 \text{ lb mol C}_2\text{H}_6\text{O}} \right| \left| \frac{454 \text{ g mol}}{1 \text{ lb mol}} \right| = \boxed{29.56 \text{ g mol C}_2\text{H}_6\text{O}}$

- 2.12 (a) $\frac{16.1 \text{ lb mol HCl}}{1 \text{ lb mol HCl}} = \boxed{588 \text{ lb HCl}}$
- (b) $\frac{19.4 \text{ lb mol KCl}}{1 \text{ lb mol KCl}} = \boxed{1466 \text{ lb KCl}}$
- (c) $\frac{11.9 \text{ g mol NaNO}_3}{1 \text{ g mol NaNO}_3} \left| \frac{85 \text{ g NaNO}_3}{1 \text{ g}} \right| \left| \frac{2.20 \times 10^{-3} \text{ lb}}{1 \text{ g}} \right| = \boxed{2.23 \text{ lb NaNO}_3}$
- (d) $\frac{164 \text{ g mol SiO}_2}{1 \text{ g mol SiO}_2} \left| \frac{60.1 \text{ g SiO}_2}{1 \text{ g}} \right| \left| \frac{2.20 \times 10^{-3} \text{ lb}}{1 \text{ g}} \right| = \boxed{21.7 \text{ lb SiO}_2}$

Solutions Chapter 2

2.13 Basis: 100 g of the compound

comp.	g	MW	g/mol	Ratio of Atoms
C	42.11	12	3.51	1.09
O	51.46	16	3.22	1
H	6.43	1.008	<u>6.38</u>	2
			13.11	

Multiply by 11 to convert the ratios into integers

The formula becomes $\text{C}_{12}\text{O}_{11}\text{H}_{22}$ Checking MW: $12(12) + 11(16) + 22(1.008) = 342$ (close enough)

Solutions Chapter 2

2.14 Vitamin A, $C_{20}H_{30}O$, Mol Wt.: 286 Vitamin C, $C_6H_8O_6$, mol. wt: 176

Vitamin A:

$$a. \quad \text{Vitamin A} = \frac{2.00 \text{ g mol}}{1 \text{ g mol}} \frac{286 \text{ g}}{454 \text{ g}} = \boxed{1.26 \text{ lb}}$$

$$\frac{16 \text{ g}}{454 \text{ g}} \frac{1 \text{ lb}}{1 \text{ lb}} = 0.0352 \text{ lb}$$

$$\text{Vitamin C} = \frac{2.00 \text{ g mol}}{1 \text{ g mol}} \frac{176 \text{ g}}{454 \text{ g}} = \boxed{0.775 \text{ lb}}$$

$$\frac{16 \text{ g}}{454 \text{ g}} \frac{1 \text{ lb}}{1 \text{ lb}} = \boxed{0.0352 \text{ lb}}$$

$$b. \quad \text{Vitamin A} = \frac{1.00 \text{ lb mol}}{1 \text{ lb mol}} \frac{286 \text{ lb}}{454 \text{ g}} = \boxed{130,000 \text{ g}}$$

$$\text{Vitamin C} = \frac{1.00 \text{ lb mol}}{1 \text{ lb mol}} \frac{176 \text{ lb}}{454 \text{ g}} = \boxed{79,900 \text{ g}}$$

$$\text{For both} \quad \frac{12 \text{ lb}}{1 \text{ lb}} \frac{454 \text{ g}}{1 \text{ lb}} = \boxed{5450 \text{ g}}$$

Solutions Chapter 2

2.15 Basis: 1000 lb oil

$$\frac{0.926 \frac{\text{lb oil}}{\text{ft}^3}}{1.00 \frac{\text{lb H}_2\text{O}}{\text{ft}^3}} \frac{62.4 \frac{\text{lb H}_2\text{O}}{\text{ft}^3}}{1 \text{ ft}^3} = 57.78 \frac{\text{lb oil}}{\text{ft}^3}$$

$$\frac{1000 \text{ lb oil}}{57.78 \text{ lb oil}} \frac{1 \text{ ft}^3 \text{ oil}}{1 \text{ ft}^3} \frac{7.48 \text{ gal}}{1 \text{ ft}^3} = 129.5 \text{ gal}$$

2.16 Basis: 10,010 lb

$$\frac{10,010 \text{ lb}}{8.80 \text{ lb}} \frac{1 \text{ gal}}{1 \text{ gal}} \frac{0.134 \text{ ft}^3}{1 \text{ ft}^3} = \boxed{152 \text{ ft}^3}$$

2.17

Basis: 1 g mol each compound

	g mol	mw	g	ρ (g/cm ³)	V (cm ³)
Pb	1	207.21	207.21	11.33	18.3
Zn	1	65.38	65.38	7.14	9.16
C	1	12.01	12.01	2.26	5.31

$$\hat{V} = \frac{\text{mass (g)}}{\text{density (g/cm}^3\text{)}}$$

Set 2 is the correct one

2.18

Basis: 10,000 SiC crystals

$$\text{volume of } 10^4 \text{ crystals: } [(0.5 \times 10^{-6} \text{ m})^2 (\pi/4) (20 \times 10^{-6} \text{ m}) (10^4)] = 3.93 \times 10^{-14} \text{ m}^3$$

$$\text{grams SiC} = (3.93 \times 10^{-14} \text{ m}^3) (3.17 \text{ g/cm}^3) (100 \text{ cm}^3/\text{m}^3) = 1.25 \times 10^{-7} \text{ g}$$

Solutions Chapter 2

2.19 (a) Volume cylinder = $\pi r^2 h = \pi (0.0125 \text{ m})^2 (1.0 \text{ m}) = 4.9 \times 10^{-4}$

Volume cylinder = Volume fiber

$4.9 \times 10^{-4} \text{ m}^2 = \pi (6.25 \times 10^{-5} \text{ m})^2 h$

$h = 40,000 \text{ m of fiber}$

Mass = (density)(volume) = $(2.25 \times 10^6 \text{ g/m}^3)(4.9 \times 10^{-4} \text{ m}^3) = \boxed{1,100 \text{ g}}$

(b) $r_{\text{coating}} = \frac{0.125 \times 10^{-3} \text{ m}}{2} + 5 \times 10^{-5} \text{ m} = 1.1 \times 10^{-4}$

$r_{\text{fiber}} = \frac{0.125 \times 10^{-3} \text{ m}}{2} = 6.25 \times 10^{-5}$

$V_{\text{fiber}} - V_{\text{coating}} = V_{\text{coating}}$

$40,000 \text{ m} ((1.1 \times 10^{-4} \text{ m})^2 \pi - (6.25 \times 10^{-5} \text{ m})^2 \pi) = 1.1 \times 10^{-3} \text{ m}^3$

$(1.1 \times 10^{-3} \text{ m}^3) \frac{1.740 \text{ kg}}{\text{m}^3} = \boxed{1.9 \text{ kg polymer}}$

2.20 The back fill must contain 1000 gal of liquid that will occupy the voids, or 1000/0.2 = 5000 gal of backfill. The empty space must be at least 10,000 gal for the tank plus 5000 gal for the backfill, or 15,000 gal equivalent to 2005 ft³.

$\frac{2005 \text{ ft}^3}{\left(\frac{1 \text{ m}}{3.281 \text{ ft}}\right)^3} \left(\frac{100 \text{ cm}}{1 \text{ m}}\right)^3 \frac{2.2 \text{ g}}{\text{cm}^3} = 1.25 \times 10^5 \text{ kg}$

2.21 $\frac{1 \text{ kg}}{5.2 \text{ m}^3} \left| \frac{1160 \text{ m}^3}{\text{kg mol}} \right| = 223.1 \text{ kg/kg mol}$

Solutions Chapter 2

2.22 Basis: 5000 bbl of 28° API oil + 20,000 bbl 15° API oil → calc. ρ_{mix} in lb_m/gal, lb_m/ft³ (assume volumes are additive); 1 bbl = 42 gal

$\rho_{\text{mix}} = \frac{\text{lb}_m \text{ 28° oil} + \text{lb}_m \text{ 15° oil}}{\text{total vol}} = \frac{\text{lb}_m \text{ 28° oil} + \text{lb}_m \text{ 15° oil}}{5000 + 20,000 \text{ bbl}}$

$SG_{28^\circ} = \frac{141.5}{28 + 131.5} = 0.887 \quad \rho_{28^\circ} = (0.887)(62.4) = \boxed{55.36 \text{ lb}_m / \text{ft}^3}$

$SG_{15^\circ} = \frac{141.5}{15 + 131.5} = 0.966 \quad \rho_{15^\circ} = (0.966)(62.4) = 60.27 \text{ lb}_m / \text{ft}^3$

$V_{28^\circ} = (5000 \text{ bbl})(42 \text{ gal / bbl})(\text{ft}^3 / 7.481 \text{ gal}) = 2.807 \times 10^4 \text{ ft}^3$

$V_{15^\circ} = (20,000)(42 \text{ gal / bbl})(\text{ft}^3 / 7.481 \text{ gal}) = 1.123 \times 10^5 \text{ ft}^3$

$\therefore \rho_{\text{mix}} = \frac{\left(55.36 \frac{\text{lb}_m \text{ 28°}}{\text{ft}^3}\right)(2.807 \times 10^4 \text{ ft}^3) + \left(60.27 \frac{\text{lb}_m \text{ 15°}}{\text{ft}^3}\right)(1.123 \times 10^5 \text{ ft}^3)}{2.807 \times 10^4 + 1.123 \times 10^5 \text{ ft}^3}$

$= \boxed{59.29 \text{ lb}_m / \text{ft}^3} = \boxed{7.93 \text{ lb}_m / \text{gal}}$

2.23 Yes

Sp. gr. $\frac{60^\circ \text{F}}{60^\circ \text{F}} = \frac{141.5}{^\circ \text{API} + 131.5} = \frac{141.5}{45.38 + 131.5} = \boxed{0.80}$

Sp. gr. $\frac{60^\circ \text{F}}{60^\circ \text{F}} \neq \text{Density}$

Solutions Chapter 2

$$2.24 \quad \frac{1.049 \text{ g/cm}^3 \text{ HAc}}{1.00 \text{ g/cm}^3 \text{ H}_2\text{O}} \left| \frac{1.00 \text{ g/cm}^3 \text{ H}_2\text{O}}{453.6 \text{ g}} \right| \left| \frac{1 \text{ lb}_m}{3.2808 \text{ ft}} \right|^3 \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^3 =$$

$$65.43 \text{ lb}_m / \text{ft}^3$$

or

$$\frac{1.049 \frac{\text{lb}_m}{\text{ft}^3} \text{ HAc}}{1.00 \frac{\text{lb}_m}{\text{ft}^3} \text{ H}_2\text{O}} \left| \frac{62.4 \frac{\text{lb}_m}{\text{ft}^3} \text{ H}_2\text{O}}{1 \text{ ft}^3 \text{ H}_2\text{O}} \right| = \boxed{65.46 \text{ lb}_m / \text{ft}^3}$$

$$2.25 \quad \rho_{\text{oil}} = \frac{(0.82) \frac{\text{lb}}{\text{ft}^3} \text{ oil}}{1 \frac{\text{lb}}{\text{ft}^3} \text{ H}_2\text{O}} \left| \frac{62.4 \frac{\text{lb}}{\text{ft}^3} \text{ H}_2\text{O}}{1 \text{ ft}^3 \text{ H}_2\text{O}} \right| = \boxed{51 \text{ lb/ft}^3 \text{ for the oil}}$$

2.26 The density of water at 25°C is 0.997 g/cm³ and at 4°C is 1.000 g/cm³. Ignore any change in density of the Ag₂O.

$$\frac{\text{g Ag}_2\text{O/cm}^3}{0.997 \text{ g H}_2\text{O/cm}^3 @ 25^\circ\text{C}} = 7.30; \text{ g Ag}_2\text{O/cm}^3 = 7.278$$

$$\frac{7.278 \text{ g Ag}_2\text{O/cm}^3}{1.000 \text{ g H}_2\text{O/cm}^3 @ 4^\circ\text{C}} = \boxed{7.278^{25}}$$

Solutions Chapter 2

2.27 Sp.gr. = 1.2185 for 30% H₂SO₄ soln

$$\rho = 1.2185 \text{ g/cm}^3$$

0.30 (1.2185) = 0.3656 g / cm³ of H₂SO₄ in the solution

$$\frac{0.3656 \text{ g}}{\text{cm}^3} \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right| = 365.6 \text{ g H}_2\text{SO}_4 / \text{L}$$

Answer: yes

2.28 Basis: 1 Day

$$\frac{200 \text{ mg HgCl}_2}{10^3 \text{ gal}} \left| \frac{7.48 \text{ gal}}{1 \text{ ft}^3} \right| \left| \frac{1 \text{ lb}}{454 \text{ g}} \right| \left| \frac{1 \text{ gmol HgCl}_2}{271.52 \text{ g HgCl}_2} \right|$$

$$\frac{1 \text{ g}}{10^3 \text{ mg}} \left| \frac{1 \text{ gmol Hg}}{\text{gmol HgCl}_2} \right| \left| \frac{200.61 \text{ g Hg}}{1 \text{ gmol Hg}} \right|$$

$$= 3.90 \times 10^{-10} \frac{\text{g Hg}}{\text{g soln}} = 3.90 \times 10^{-4} \text{ ppm}$$

This discharge for 1 analysis is just below the prescribed limit. If more than one analysis is made per day, a violation occurs.

Solutions Chapter 2

2.29 Basis: 1 L of 0.10 molar H_2SO_4 solution = 1 L soln MW $\text{H}_2\text{SO}_4 = 98.08$

$$\rho_{\text{soln}} = 1.858 \text{ g } 96\% \text{ soln/cm}^3 \text{ } 96\% \text{ soln, since sp. gr.} = 1.858$$

$$(a) \frac{0.10 \text{ g mol } \text{H}_2\text{SO}_4}{1 \text{ L soln}} \left| \frac{98.08 \text{ g } \text{H}_2\text{SO}_4}{1 \text{ g mol } \text{H}_2\text{SO}_4} \right| \frac{1.00 \text{ g } 96\% \text{ soln}}{0.96 \text{ g } \text{H}_2\text{SO}_4} = \frac{10.22 \text{ g } 96\% \text{ soln}}{1 \text{ L soln}}$$

$$(b) \frac{1 \text{ cm}^3 96\% \text{ soln}}{1.858 \text{ g } 96\% \text{ soln}} \left| \frac{10.22 \text{ g } 96\% \text{ soln}}{1 \text{ L soln}} \right| = \frac{5.50 \text{ cm}^3 96\% \text{ soln/L soln}}{1 \text{ L soln}}$$

(c) Assume no volume change on mixing for such a dilute solution

	g	cm ³
96% H_2SO_4 soln	10.22	5.50
H_2O	994.5	994.5
	1004.7	1000

$$\rho_{\text{soln}} = \frac{1004.7}{1000} = 1.0047 \text{ g/cm}^3$$

2.30 $\rho_{\text{ice}} = 0.917 \text{ g/cm}^3$ Density of ice

$\rho_{\text{H}_2\text{O}} = 1.00 \text{ g/cm}^3$ Density of $\text{H}_2\text{O}(l)$

$\rho_{\text{alcohol}} = 0.791 \text{ g/cm}^3$ Density of pure alcohol

If the rum is 97 proof (48.5% EtOH), the density is 0.917 g/cm³. As the proof rises, the density of the solutions decreases below that of ice, causing the ice to sink.

Solutions Chapter 2

2.31 $\rho_{\text{water at } 60^\circ\text{F}} = 0.99905 \text{ g/mL}$

$$\text{Sp. gr. of benzene at } 60^\circ\text{F} = \frac{0.879 \text{ g/cm}^3}{0.99905 \text{ g/cm}^3} = \boxed{0.879}$$

2.32

$$a. \frac{0.90 \frac{\text{kg liq.}}{\text{m}^3}}{\frac{\text{kg } \text{H}_2\text{O}}{\text{m}^3}} \left| \frac{10^3 \frac{\text{kg } \text{H}_2\text{O}}{\text{m}^3}}{1 \text{ m}^3} \right| = \frac{900 \frac{\text{kg liq.}}{\text{m}^3}}{1 \text{ m}^3}$$

$$b. \frac{1 \text{ m}^3}{900 \text{ kg liq.}} \left| \left(\frac{3.2808 \text{ ft}^3}{1 \text{ m}^3} \right)^3 \right| \frac{0.454 \text{ kg}}{1 \text{ lb}_m} = \frac{0.0178 \frac{\text{ft}^3}{\text{lb}_m}}{1 \text{ lb}_m}$$

$$c. \frac{0.9(1000 \text{ g})}{\text{liter}} \left| \frac{1.5 \text{ liter}}{1} \right| + 232 \text{ g} = \boxed{1582 \text{ g}}$$

2.33 Basis: 1.704 kg HNO_3 1 kg H_2O

a. Comp. Kg mass fraction weight percent

HNO_3	1.704	0.63	63
H_2O	1	0.37	37
Total	2.704	1.00	37

b. Ignore the change of density of water with temperature

$$\frac{0.63 \text{ lb } \text{HNO}_3}{1 \text{ lb soln}} \left| \frac{1.382 \text{ lb soln}}{1 \text{ ft}^3 \text{ soln}} \right| \frac{62.4 \text{ lb } \text{H}_2\text{O}}{1 \text{ ft}^3 \text{ H}_2\text{O}} = \frac{54.3 \text{ lb } \text{HNO}_3}{\text{ft}^3 \text{ soln}}$$

Solutions Chapter 2

$$c. \frac{1.382 \text{ g soln}}{1 \text{ cm}^3 \text{ soln}} \left| \frac{1.00 \text{ g H}_2\text{O}}{1 \text{ cm}^3 \text{ H}_2\text{O}} \right| \frac{0.63 \text{ g HNO}_3}{\text{g soln}} \left| \frac{1 \text{ g mol HNO}_3}{63 \text{ g HNO}_3} \right| \frac{10^3 \text{ cm}^3}{1 \text{ L}} =$$

$$\frac{13.8 \text{ g mol}}{\text{L}}$$

2.34

$$\text{Density of acetaldehyde} = \frac{\text{kg}}{\text{m}^3} = 783$$

$$\text{volume of acetaldehyde} = \frac{113.0 \text{ kg}}{783 \text{ kg acetaldehyde}} \times 1 \text{ m}^3$$

$$= 0.144 \text{ m}^3$$

$$\text{maximum required volume} = 0.144 \text{ cm}^3$$

$$\text{volume of vessel} = \text{max. required volume} = \frac{4}{3} \pi r^3$$

$$r = \sqrt[3]{\frac{3}{4\pi} \times (0.144 \text{ m}^3)} = 0.33 \text{ m}$$

A spherical vessel with a radius of 0.33 m could be used to store the liquid.

$$2.35 \quad \text{Specific gravity} = 0.792 \left(\text{g} \frac{\text{MeOH}}{\text{cm}^3} \right)$$

$$\frac{0.500 \text{ L}}{1 \text{ L}} \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right| \frac{0.792 \text{ g MeOH}}{\text{cm}^3} \left| \frac{1 \text{ lb}}{454 \text{ g}} \right| \frac{16 \text{ Oz}}{1 \text{ lb}} = 13.96 \text{ Oz}$$

Yes

Solutions Chapter 2

2.36

$$Q = vA = \frac{56.7 \text{ ft}}{\text{s}} \left| \frac{\pi (6 \text{ in})^2}{4} \right| \frac{\text{ft}^2}{144 \text{ in}^2} \left(\frac{0.3048 \text{ m}}{\text{ft}} \right)^3 = 0.316 \text{ m}^3/\text{s}$$

2.37

Basis: 40,000 lb fuel

$$\frac{40,000 \text{ lb fuel}}{0.91 \frac{\text{lb fuel}}{\text{ft}^3 \text{ fuel}}} \left| \frac{1.0 \frac{\text{lb H}_2\text{O}}{\text{ft}^3 \text{ H}_2\text{O}}}{62.4 \frac{\text{lb H}_2\text{O}}{\text{ft}^3 \text{ H}_2\text{O}}} \right| \frac{7.48 \text{ gal}}{1 \text{ ft}^3} \left| \frac{1 \text{ min}}{40 \text{ gal}} \right| = 132 \text{ min}$$

2.38

Basis: 100 g of compound

	C	H	O
Mass (m) combining / g	26.9	2.2	70.9
Molar mass (M) / g mol ⁻¹	12	1	16
Number of moles combining (mass + molar mass)	26.9 / 12 = 2.24	2.2 / 1 = 2.20	70.9 / 16 = 4.43
Ratio of number of moles	2.24 / 2.20 = 1.02	2.20 / 2.20 = 1.00	4.43 / 2.20 = 2.01
Simplest ratio	1	1	2

The empirical formula of this organic compound is C₁H₁O₂.

Solutions Chapter 2

- 2.39 1. Basis: 100 g sample: 49.5 g C; 5.2 g H; 28.8 g N; 16.5 g O
2. Divide each mass number by the molar mass:
 (49.5 g C / 12.011 g/mol C) = 4.121 gmol C
 (5.2 g H / 1.008 g/mol H) = 5.159 gmol H
 (28.8 g N / 14.007 g/mol N) = 2.056 gmol N
 (16.5 g O / 15.999 g/mol O) = 1.031 gmol O
3. Divide each molar amount by the smallest molar amount
 (4.121 mol C / 1.031 mol O) = (4 mol C/mol O)
 (5.159 mol H / 1.031 mol O) = (5 mol H/mol O)
 (2.056 mol N / 1.031 mol O) = (2 mol N/mol O)
 (1.031 mol O / 1.031 mol O) = (1 mol O/mol O)

4. Empirical Formula is then



Component	g/mol	mol fraction	MW	g	mass fraction
Na	1	0.20	23	23	0.22
Cl	1	0.20	35.45	35.45	0.33
O	3	0.60	16	48	0.45
	5			106.45	1.00

Solutions Chapter 2

2.41 Basis: 1 gal of solution.

Mass of solution:

$$\frac{1.0824 \text{ lb soln}}{\text{ft}^3 \text{ H}_2\text{O}} \left| \frac{62.4 \text{ lb H}_2\text{O}}{\text{ft}^3 \text{ H}_2\text{O}} \right| \frac{1 \text{ ft}^3}{7.48 \text{ gal}} \left| \frac{1 \text{ gal}}{1 \text{ ft}^3} \right| = \boxed{9.03 \text{ lb soln}}$$

$$\text{Mass fraction KOH} = \frac{0.813 \text{ lb}}{9.03 \text{ lb}} = \boxed{0.09}$$

$$\text{Mass fraction H}_2\text{O} = 1 - 0.09 = \boxed{\frac{0.91}{1.00} \text{ Total}}$$

2.42 Mass fraction to mole fraction:

$$x_1 = \frac{\frac{a_1}{\text{MW}_1}}{\frac{a_1}{\text{MW}_1} + \frac{(1-a_1)}{\text{MW}_2}}$$

Mole fraction to mass fraction

$$a_1 = \frac{x_1 \text{MW}_1}{(x_1 \text{MW}_1) + (1-x_1) \text{MW}_2}$$

Solutions Chapter 2

2.43 Basis: 100 kg mol gas

Comp.	Mol % = mol	MW	kg
CH ₄	30	16	480
H ₂	10	2	20
N ₂	60	28	1680
Total	100		2180

$$\frac{21.8 \text{ kg}}{\text{kg mol}}$$

2.44 Basis: 100 g mol gas

Comp.	mol = %	MW	g
CO ₂	19.3	44	849.2
N ₂	72.1	28	2018.8
O ₂	6.5	32	208.0
H ₂ O	2.1	18	37.8
	100.0		3113.8

$$\text{Avg. mol. wt} = \frac{3113.8}{100.0} = \boxed{31.138}$$

2.45 Basis: 100 lb mol

Comp.	% = mol	MW	lb
CO ₂	16	44	2640
CO	10	28	280
N ₂	30	28	840
			3760

$$\text{Avg. MW} = 37.6 \text{ lb/lb mol}$$

Solutions Chapter 2

2.46 Basis: 30 lb gas

Comp.	lb	MW	lb mol	mol fr.
CO ₂	20	44	0.455	0.56
N ₂	10	28	0.357	0.44
	30		0.812	1.00

2.47 a) ☒ 1000

b) ☒ No

c) Yes, because for solids and liquids the ratio in ppb is mass whereas for gases the ratio is in moles.

2.48 On a paper free basis the total ppm are:

Brand A: 6060 ppm Brand B: 405 ppm

The respective mass fractions are:

The other entries are similar

	Fe	Cu	Pb
Brand A:	$\frac{1310}{6060} = 0.216$	$\frac{2000}{6060} = 0.330$	$\frac{2750}{6060} = 0.454$
Brand B:	$\frac{350}{405} = 0.864$	$\frac{50}{405} = 0.123$	$\frac{5}{405} = 0.0123$

Solutions Chapter 2

2.49 Basis: 190,000 ppm

$$\frac{190,000 \text{ g PCB}}{10^6} \times 100 = \boxed{19\%}$$

2.50 Yes. Bases are first entries.

$$\frac{4800 \text{ g mol CCl}_4}{10^9 \text{ g mol air}} \left| \frac{10^3 \text{ g mol air}}{\text{kg mol air}} \right| \left| \frac{\text{kg mol air}}{22.8 \text{ m}^3} \right| \left| \frac{154 \text{ g CCl}_4}{\text{g mol CCl}_4} \right| \left| \frac{103 \text{ mg CCl}_4}{\text{g CCl}_4} \right| =$$

32.4 mg CCl₄/m³ which exceeds the NIOSH standards

Solutions Chapter 2

2.51

$$\text{a. } \frac{25,600 \text{ ton P}}{\text{yr}} \left| \frac{2.6 \text{ yr}}{1} \right| \left| \frac{1}{1.2 \times 10^{14} \text{ gal}} \right| \left| \frac{1 \text{ gal}}{3.785 \text{ L}} \right| \left| \frac{2000 \text{ lb}}{1 \text{ ton}} \right| \left| \frac{454 \text{ g}}{1 \text{ lb}} \right| \left| \frac{10^6 \mu \text{ g}}{1 \text{ g}} \right|$$

$$= \boxed{133.1 \mu \text{ g/L}}$$

$$\text{b. } \frac{19,090 \text{ lb(P)}_{\text{municipal}}}{30,100 \text{ lb(P)}_{\text{total}}} = \boxed{63.4\%}$$

$$\text{c. } \frac{19,090 \text{ lb(P)}_{\text{municipal}}}{30,100 \text{ lb(P)}_{\text{total}}} \left| \frac{0.70 \text{ lb(P)}_{\text{det.}}}{1 \text{ lb(P)}_{\text{municipal}}} \right| \left| \frac{100 \text{ lb(P)}_{\text{total}}}{30,100 \text{ lb(P)}_{\text{total}}} \right| = \boxed{44.4\%}$$

For d. and e. assume that (P)outflow remains unchanged.

$$\text{d. } \text{P retained/yr} = 2,240 + 6,740 + 0.7 \times 19,090 - 4,500 = 17,843 \text{ ton/yr.}$$

P conc. in ppb =

$$\frac{17,843 \text{ ton}}{\text{yr}} \left| \frac{2.6 \text{ yr}}{1} \right| \left| \frac{1}{1.2 \times 10^{14} \text{ gal}} \right| \left| \frac{2000 \text{ lb}}{\text{ton}} \right| \left| \frac{1 \text{ g/cm}^3}{8.345 \text{ lb/gal}} \right| \left| \frac{10^9 \text{ g}}{1 \text{ billion g}} \right| = 92.6 \text{ ppb}$$

This is greater than 10 ppb. Eutrophication will not be reduced.

$$\text{e. } \text{P retained/yr} = 2,240 + 6,740 + 0.3 \times 19,090 - 4,500 = 10,207 \frac{\text{ton}}{\text{yr}}$$

P conc. in ppb =

$$\frac{10,207 \text{ ton}}{\text{yr}} \left| \frac{2.6 \text{ yr}}{1} \right| \left| \frac{1}{1.2 \times 10^{14} \text{ gal}} \right| \left| \frac{2000 \text{ lb}}{\text{ton}} \right| \left| \frac{1 \text{ g/cc}}{8.345 \text{ lb/gal}} \right| \left| \frac{10^9 \text{ g}}{1 \text{ billion g}} \right| = 53.2 \text{ ppb}$$

This will not help.

Solutions Chapter 2

2.52

Basis: 10^6 g mol gas

$$\frac{350 \text{ g mol H}_2\text{S}}{10^6 \text{ g mol gas}} \left| \frac{1 \text{ g mol gas}}{1 \text{ g mol CO}_2} \right| \frac{34 \text{ g H}_2\text{S}}{1 \text{ g mol H}_2\text{O}} \left| \frac{1 \text{ g mol CO}_2}{44 \text{ g CO}_2} \right|$$

$$= \frac{270}{10^6} \frac{\text{g H}_2\text{S}}{\text{g CO}_2} = \frac{270}{10^6} \frac{\text{g H}_2\text{S}}{\text{g total liquid}}$$

$$\text{mass fraction H}_2\text{S} = \boxed{2.70 \times 10^{-4}}$$

2.53

(a) $\frac{1 \text{ mol O}_2}{100 \text{ mol gas}} \Rightarrow \frac{10^4 \text{ mol O}_2}{10^6 \text{ mol gas}}$ or 10^4 ppm

(b) Basis: 100 mol gas

answer

Comp.	% = mol	mol fr.	or mol %
SO ₃	55	0.932	93.2
SO ₂	3	0.051	5.1
O ₂	<u>1</u>	<u>0.017</u>	<u>1.7</u>
Total	59	1.000	100.0

Solutions Chapter 2

2.54

MW	CaCO ₃ :	100.06
	Ca	40.05
	Mg	24.3
	C	12.01
	O	16.00

$$\frac{100.06 \text{ g CaCO}_3}{\text{g mol Ca CO}_3} \left| \frac{1 \text{ g mol CaCO}_3}{1 \text{ g mol Ca}} \right| \frac{1 \text{ g mol Ca}}{40.05 \text{ g Ca}} = 2.50 \frac{\text{g CaCO}_3}{\text{g Ca}}$$

$$\text{Similarly } \frac{\text{g CaCO}_3}{\text{g Mg}} = 4.118 \frac{\text{g CaCO}_3}{\text{g Mg}}$$

$$\text{Total alkalinity} = 2.50 (56.4) + 4.118 (8.8) = \boxed{177 \frac{\text{mg CaCO}_3}{\text{L}}}$$

2.55

$$\text{Total dosage} = 27 \text{ lb} / 0.75 \text{ mil gal} = 36 \text{ lb} / \text{mil gal} = 36 \text{ lb} / \text{mil gal} \times \frac{1 \text{ mg/L}}{8.34 \text{ lb} / \text{mil gal}} = 4.3 \text{ mg/L}$$

$$\text{Residual Cl}_2 = 4.3 \text{ mg/L} - 2.6 \text{ mg/L} = 1.7 \text{ mg/L}$$

2.56 No. 1 molecule in 10^{13} or more is not 13-20 ppb

2.57 On a mol basis, the carbon dioxide concentration in air is about 350 parts per million (ppm), while that of oxygen is about 209,500 ppm. If the atmospheric concentration of carbon dioxide is increasing at about 1% per year (i.e., from 350 ppm this year to 353.5 ppm next year), and not to 1%, the 3.5-ppm change in dioxide concentration causes the oxygen concentration to fall from 209,500 to about 209,497 ppm, which is less than a 0.002% decrease. So, there is no need to worry about an oxygen deficit at present.

Solutions Chapter 2

2.58

Basis: 100 g of the sample

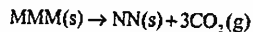
The biomass sample is

g = % dry weight of cells

C	50.2
O	20.1
N	14.0
H	8.2
P	<u>3.0</u>
	95.5
other	<u>4.5</u>
Total	100.0

$$\frac{10.5 \text{ g cells}}{\text{g mol ATP}} \left| \frac{50.2 \text{ g C}}{100 \text{ g cells}} \right| \left| \frac{1 \text{ g mol C}}{12 \text{ g C}} \right| = 0.439 \text{ g mol C/g mol ATP}$$

2.59



$$\text{a. } \frac{2 \times 10^7 \text{ disintegrations}}{\text{min}} \left| \frac{1 \text{ min}}{60} \right| \left| \frac{1 \text{ curie}}{3 \times 10^{10} \text{ disintegrations/s}} \right| \left| \frac{10^6 \mu \text{ curie}}{1 \text{ curie}} \right| = 11 \mu \text{ curie}$$

$$\text{b. } \frac{2 \times 10^7 \text{ disintegrations}}{\text{min}} \left| \frac{0.80}{1} \right| = \boxed{1.6 \times 10^7 \text{ cpm}}$$

Solutions Chapter 2

2.60

The relation to use is

$$t_{1/2} = \ln(2)/(k)(\text{OH}^-)$$

with $(\text{OH}^-) = 1.5 \times 10^6$

	<u>k</u>	<u>$t_{1/2}(\text{seconds})$</u>
Methanol	0.15×10^{-12}	30.8×10^5
Ethanol	1×10^{-12}	4.6×10^5
MTBE	0.60×10^{-12}	7.7×10^5

The order is in increasing persistence ethanol, MTBE, and methanol.

Solutions Chapter 3

- 3.1 (a) A gas requires a convenient basis of 1 or 100 g moles or kg moles (if use SI units).
- (b) A gas requires a convenient basis of 1 or 100 lb moles (if use AE units).
- (c) Use 1 or 100 kg of coal, or 1 or 100 lb of coal because the coal is a solid and mass is a convenient basis.
- (d) Use 1 or 100 moles (SI or AE) as a convenient basis as you have a gas.
- (e) Same answer as (e).

3.2 Since the mixture is a gas, use 1 or 100 moles (SI or AE) as the basis.

3.3 Pick one day as a basis which is equivalent to what is given -- two numbers:

- (a) 134.2 lb Cl (b) 10.7×10^6 gal water.

Solutions Chapter 4

4.1 $T_K = -10 + 273 = 263K$
 $T^{\circ}F = -10(1.8) + 32 = 14^{\circ}F$
 $T^{\circ}R = 14 + 460 = 474^{\circ}R$

4.2 Yes, if the temperature scale is a linear relative one ($^{\circ}C$, $^{\circ}F$), or a logarithmic scale ($\ln 1^{\circ}$ is zero). No, if the scale is absolute, but read J. Wisniak, *J. Chem. Educ.*, 77, 518-522 (2000) for a different conclusion.

4.3 $C_p = 8.41 + \frac{2.4346 \times 10^{-5} T_K}{\left(\frac{2.4346 \times 10^{-5} \frac{J}{(gmol)(K)^2} \right) (T_K)}$

Substitute $1.8 T_K = T^{\circ}R$

$$C_p = 8.41 + 2.4346 \times 10^{-5} \frac{J}{(gmol)(K)^2} \left(\frac{T^{\circ}R}{1.8} \right)^2$$

$$= 8.41 + 1.353 \times 10^{-5} T^{\circ}R$$

4.4 a) $\frac{10^{\circ}C | 1.8^{\circ}F}{1.0^{\circ}C} + 32 = 50^{\circ}F$

b) $\frac{10^{\circ}C | 1.8^{\circ}F}{1.0^{\circ}C} + 32 + 460^{\circ}R = 510^{\circ}R$

c) $\frac{-25^{\circ}F - 32^{\circ}F}{1.8} \left| \frac{1.0^{\circ}C}{1.8^{\circ}F} \right| + 273K = 241.3K$

d) $\frac{150K | 1.8^{\circ}R}{1.0K} = 270^{\circ}R$

Solutions Chapter 4

4.5 First multiply the RHS of the equation so that

$\frac{Btu}{(lbmol)(^{\circ}F)}$	$\frac{1054.8J}{1 Btu}$	$\frac{1 lb mol}{454 gmol}$	$\frac{1.8^{\circ}F}{1.0^{\circ}C}$	$\frac{1^{\circ}C}{1K}$
----------------------------------	-------------------------	-----------------------------	-------------------------------------	-------------------------

$$= 4.182 \frac{J}{(gmol)(^{\circ}K)}$$

and substitute $T^{\circ}F = 1.8T^{\circ}C + 32$

$$C_p = \left[8.448 + 0.5757 \times 10^{-2} (1.8T^{\circ}C + 32) - 0.2159 \times 10^{-5} (1.8T^{\circ}C + 32)^2 + 0.3059 \times 10^{-9} (1.8T^{\circ}C + 32)^3 \right] 4.182 \frac{J}{(gmol)(^{\circ}K)}$$

Simplifying,

$$C_p = 36.05 + 0.0447T - 0.2874 \times 10^{-4} T^2 + 0.7424 \times 10^{-8} T^3$$

4.6 The instrument does not contain mercury, but has to contain a fluid that responds at $-76^{\circ}C$ and can be calibrated to measure temperature.

4.7 The first sentence really means that the unit interval $\Delta^{\circ}C =$ the unit interval ΔK . However, $^{\circ}C \neq K$ as a temperature measure. The second sentence is satisfactory when referred to temperature, but the "only difference" should be omitted. Third sentence: there is no difference in the precision but the reported value of temperature may be rounded off to leave fewer significant figures (unlikely as much as one digit).

Solutions Chapter 4

4.8 Basis: given temperatures*

	°F	°R	K	°C
a.	140*	600	333	60
b.	77	537	298*	25
c.	40	500*	277.8	4.5
d.	-40	420	233	-40*
e.	1000*	1460	811	538
f.	540	1000*	555	282
g.	1340	1800	1000*	727
h.	1832	2292	1273	1000*

4.9 Basis: $0.171 \times 10^{-8} \frac{\text{Btu}}{(\text{ft})^2 (\text{hr})(^\circ\text{R})^4}$

$$\frac{0.17 \times 10^{-8} \text{ Btu}}{(\text{ft})^2 (\text{hr})(^\circ\text{R})^2} \left| \frac{(1.8^\circ\text{R})^4}{(1 \text{ K})^4} \right| \left| \frac{\text{hr}}{3600 \text{ s}} \right| \left| \frac{(\text{ft})^2}{144 (\text{in})^2} \right| \left| \frac{(\text{in})^2}{(2.54 \text{ cm})^2} \right| \left| \frac{(100 \text{ cm})^2}{(1 \text{ m})^2} \right| \left| \frac{1.055 \times 10^3 \text{ J}}{1 \text{ Btu}} \right| =$$

$$\boxed{\frac{5.67 \times 10^{-8} \text{ J}}{(\text{m})^2 (\text{s})(\text{K})^4}}$$

4.10 Yes, if the fluid expansion is linear with temperature.

4.11 You do not get a straight line with p vs. $1/T$, but do so with $\ln p$ vs. $1/T$.
At $p = 1340 \text{ mm Hg}$, $T = 384 \text{ K}$; $a = 20.36$ and $b = -5.12 \times 10^3$ with the units of K.

Solutions Chapter 5

Basis: 15 cm³ water

5.1

$$a. \quad m = \rho V = \frac{1000 \text{ kg}}{\text{m}^3} \left| \frac{10 \text{ m}}{1} \right| \left| \frac{10 \text{ m}}{1} \right| \left| \frac{0.15 \text{ m}}{1} \right| = 15,000 \text{ kg}$$

$$b. \quad \frac{F}{A} = \frac{m g}{A} = \frac{15,000 \text{ kg}}{1} \left| \frac{9.80 \text{ m}}{\text{s}^2} \right| \left| \frac{1 \text{ N}}{1 \text{ (kg)(m)}} \right| \left| \frac{1 \text{ Pa}}{1 \text{ N}} \right| = 1470 \text{ Pa}$$

$$= 1.47 \text{ kPa}$$

$$\frac{1.470 \text{ kPa}}{101.3 \text{ kPa}} \left| \frac{1 \text{ atm}}{1} \right| \left| \frac{14.7 \text{ psi}}{1 \text{ atm}} \right| = 0.21 \text{ psi}$$

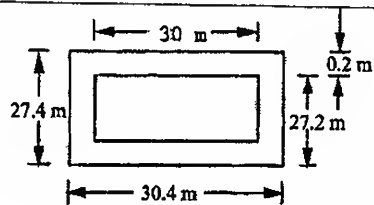
$$\text{or} \quad \frac{15 \text{ cm H}_2\text{O}}{2.54 \text{ cm}} \left| \frac{1 \text{ in.}}{1} \right| \left| \frac{1 \text{ ft}}{12 \text{ in.}} \right| \left| \frac{14.696 \text{ psi}}{33.91 \text{ ft H}_2\text{O}} \right| = 0.21$$

5.2

$$\rho_{\text{concrete}} = 2080 \text{ kg/m}^3$$

$$\rho_{\text{water}} = 1000 \text{ kg/m}^3$$

Volume of concrete:



Sides

$$V_s = \frac{5 \text{ m}}{1} \left| \frac{30.2 \text{ m}}{1} \right| \left| \frac{200 \text{ mm}}{1000 \text{ mm}} \right| \left| \frac{1 \text{ m}}{1} \right| \left| \frac{2 \text{ sides}}{1} \right| = 60.4 \text{ m}^3$$

Ends

Solutions Chapter 5

$$V_e = \frac{5 \text{ m}}{1} \left| \frac{27.2 \text{ m}}{1} \right| \left| \frac{200 \text{ mm}}{1000 \text{ mm}} \right| \left| \frac{1 \text{ m}}{1} \right| \left| \frac{2 \text{ ends}}{1} \right| = 54.4 \text{ m}^3$$

Floor

$$V_f = \frac{27.4 \text{ m}}{1} \left| \frac{30.4 \text{ m}}{1} \right| \left| \frac{200 \text{ mm}}{1000 \text{ mm}} \right| \left| \frac{1 \text{ m}}{1} \right| = 166.592 \text{ m}^3$$

$$\text{Total volume} = 281.392 \text{ m}^3$$

$$\text{Mass of concrete} = \frac{281.392 \text{ m}^3}{1} \left| \frac{2080 \text{ kg}}{\text{m}^3} \right| = 585,295$$

Volume of displaced water required to float:

$$\frac{586,543.36 \text{ kg}}{1000 \text{ kg H}_2\text{O}} \left| \frac{1 \text{ m}^3 \text{ H}_2\text{O}}{1} \right| = 586.543 \text{ m}^3$$

$$V = LWh \rightarrow h = \frac{V}{LW}$$

$$h = \frac{586.54 \text{ m}^3}{27.4 \text{ m} \times 30.4 \text{ m}} = 0.703 \text{ m}$$

Solutions Chapter 5

5.3 The pressure is a gauge pressure.

Basis: 50.0 psig

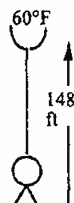
$$a. \quad \frac{50.0 \text{ psig}}{14.7 \text{ psia}} \left| \frac{33.91 \text{ ft H}_2\text{O}}{14.7 \text{ psia}} \right| =$$

115 ft

(difference)

b. No. Insufficient height

Alternate solutions can be applying $\Delta p = \rho \Delta h g$



$$5.4 \quad p = \rho g h \text{ so } h_{\text{Hg}} = h_{\text{kero}} \frac{\rho_{\text{kero}}}{\rho_{\text{Hg}}} ; \rho_{\text{kero}} = \frac{0.82}{1.00} \frac{\text{g}}{\text{cm}^3}$$

Basis: 5 in kerosine

$$\frac{5.0 \text{ in kero}}{1 \text{ in}} \left| \frac{25.4 \text{ mm}}{1 \text{ in}} \right| \left| \frac{0.82 \text{ g/cm}^3}{13.6 \text{ g/cm}^3} \right| = 7.66 \text{ mm Hg}$$

5.5

$$\frac{\text{lb}_f}{\text{in}^2} \left| \frac{\text{in}^2}{\text{in}^2} \right| = \text{lb}_f \rightarrow \text{lb}_m \text{ in the AE system}$$

so the procedure is ok, although the unit conversion is ignored.

Solutions Chapter 5

5.6 The equation is

$$\Delta p = 4 f \rho \left[(v^2 / 2g) (L/D) \right]$$

The units on the right hand side (with f dimensionless) in SI are

$$\frac{\rho \frac{\text{kg}}{\text{m}^3}}{\left(\frac{\frac{\text{m}^2}{\text{s}^2}}{\frac{(\text{kg})(\text{m})}{\text{s}^2}} \right) \left(\frac{\text{m}}{\text{m}} \right)} \rightarrow \frac{1}{\text{m}^2}$$

hence the equation is not dimensionally consistent because Δp has the units of N/m^2 . If g is replaced with g_c , the units would be correct.

Solutions Chapter 5

5.7 $Q = 0.61S\sqrt{(2\Delta p)/\rho}$ assume hole is open to atmosphere

$$\Delta p = \frac{144 \text{ in}^2}{1 \text{ ft}^2} \left[\frac{23 \text{ lb}_t}{\text{in}^2} + \frac{73 \text{ in. gas}}{1 \text{ gas}} \left| \frac{0.703 \text{ H}_2\text{O}}{1 \text{ gas}} \right| \frac{1 \text{ ft}}{12 \text{ in}} \left| \frac{14.7}{33.91} \right| \frac{\text{lb}_t}{\text{in}^2} \right]$$

$$= 3,579 \text{ lb}_t/\text{ft}^2$$

$$\rho = \frac{0.703 \frac{\text{lb}}{\text{ft}^3}}{1 \text{ lb}/\text{ft}^3 \text{ H}_2\text{O}} \left| \frac{62.4 \frac{\text{lb H}_2\text{O}}{\text{ft}^3 \text{ H}_2\text{O}}}{1 \text{ lb}/\text{ft}^3 \text{ H}_2\text{O}} \right| = 43.87 \frac{\text{lb}_m}{\text{ft}^3}$$

$$S = \frac{\pi}{4} \left(\frac{1}{(4)(12)} \right)^2 = 3.409 \times 10^{-4}$$

$$Q = (3600)(0.61)(3.409 \times 10^{-4})\sqrt{(2)(3579)\text{g}_c/43.87} = \boxed{54.6 \frac{\text{ft}^3}{\text{hr}}}$$

Solutions Chapter 5

5.8 Basis: Dept = 1000 m $p = p_o + \rho gh$

$$p = 1 \text{ atm} +$$

$$\frac{1000 \text{ m}}{1 \text{ cm}^3} \left| \frac{1.024 \text{ g}}{\text{cm}^3} \right| \frac{9.8 \text{ m}}{\text{s}^2} \left| \frac{1 \text{ kg}}{10^3 \text{ g}} \right| \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^3 \left| \frac{1 \text{ N}}{(\text{kg})(\text{m})/\text{s}^2} \right| \left| \frac{1 \text{ kPa}}{1 \text{ N}} \right| \left| \frac{1 \text{ atm}}{1.013 \times 10^5 \text{ N/m}^2} \right|$$

$$= \frac{100.1 \text{ atm}}{1 \text{ atm}} \left| \frac{101.3 \text{ kPa}}{1 \text{ atm}} \right| = \boxed{1.014 \times 10^4 \text{ kPa}}$$

Alternative solution:

$$101.3 \text{ kPa} + \frac{1000 \text{ m sea H}_2\text{O}}{1.00 \text{ g sea H}_2\text{O}} \left| \frac{1.024 \text{ g H}_2\text{O}}{\text{cm}^3} \right| \frac{3.28 \text{ ft}}{1 \text{ m}} \left| \frac{101.3 \text{ kPa}}{33.91 \text{ ft H}_2\text{O}} \right| = 1.003 \times 10^4$$

$$+ 0.01 \times 10^4$$

$$= 1.013 \times 10^4$$

5.9 (a) $p_{\text{ABS}} = p_{\text{Gauge}} + p_{\text{atm}}$

$$\left(\frac{22.4 \text{ lb}_t}{1 \text{ in}^2} \left| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right| \right) + \left(\frac{28.6 \text{ in. Hg}}{1} \left| \frac{14.7 \text{ psia}}{29.92 \text{ in. Hg}} \right| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right) = \boxed{5250 \text{ lb}_t/\text{ft}^2}$$

$$(b) \left(\frac{22.4 \text{ psig}}{1} \left| \frac{29.92 \text{ in. Hg}}{14.7 \text{ psia}} \right| \right) + 28.6 \text{ in. Hg} = \boxed{74.2 \text{ in. Hg}}$$

$$(c) \left(\frac{22.4 \text{ psig}}{1} \left| \frac{1.013 \times 10^4 \text{ N/m}^2}{14.7 \text{ psia}} \right| \right) + \left(\frac{28.6 \text{ in. Hg}}{1} \left| \frac{1.013 \times 10^4 \text{ N/m}^2}{27.92 \text{ in. Hg}} \right| \right) = \boxed{2.51 \times 10^5 \text{ N/m}^2}$$

$$(d) \left(\frac{22.4 \text{ psig}}{1} \left| \frac{33.91 \text{ ft H}_2\text{O}}{14.7 \text{ psia}} \right| \right) + \left(\frac{28.6 \text{ in. Hg}}{1} \left| \frac{33.91 \text{ ft H}_2\text{O}}{29.92 \text{ in. Hg}} \right| \right) = \boxed{84.1 \text{ ft H}_2\text{O}}$$

Solutions Chapter 5

5.10 Neither John is necessarily right. The pressure at the top of Pikes Peak is continually changing.

5.11 $\Delta p = \rho gh$

$$a. \quad \frac{1 \text{ g}}{\text{cm}^3} \left| \frac{9.8 \text{ m}}{\text{s}^2} \right| \frac{13.1 \text{ m}}{1000 \text{ g}} \left| \frac{1 \text{ kg}}{\text{m}^3} \right| \frac{(100 \text{ cm})^3}{\text{m}^3} \left| \frac{\text{Pa}}{\frac{1 \text{ kg}}{\text{m s}^2}} \right| \left| \frac{1 \text{ kPa}}{1000 \text{ Pa}} \right|$$

$$= 128.4 \text{ kPa}$$

$$b. \quad \frac{F}{A} = \frac{mg}{A_{\text{Bottom}}} = \frac{\rho V g}{A_{\text{Bottom}}} = \frac{\rho(S.A.)(t)g}{A_{\text{Bottom}}}$$

$$A_{\text{Bottom}} = \frac{\pi}{4} D^2 = \frac{\pi}{4} (30.5 \text{ m})^2 = 730.62 \text{ m}^2$$

$$A_{\text{Top}} = 730.62 \text{ m}^2$$

$$A_{\text{side}} = \pi Dh = \pi(30.5 \text{ m})(13.1 \text{ m}) = 1255.2 \text{ m}^2$$

$$S.A. = A_{\text{Top}} + A_{\text{Bottom}} + A_{\text{Side}}$$

Solutions Chapter 5

$$= (730.62 + 730.62 + 1255.22) \text{ m}^2 = 2716.46 \text{ m}^2$$

$$\frac{\rho(S.A.)(t)g}{A} =$$

$$\frac{7.86 \text{ g}}{\text{cm}^3} \left| \frac{(100 \text{ cm})^3}{\text{m}^3} \right| \frac{2,716.46 \text{ m}^2}{730.6 \text{ m}^2} \left| \frac{9.35 \times 10^{-3} \text{ m}}{\text{s}^2} \right| \left| \frac{9.8 \text{ m}}{\text{s}^2} \right|$$

$$\frac{1 \text{ kg}}{1000 \text{ g}} \left| \frac{1 \text{ Pa}}{1 \text{ kg/ms}^2} \right| \left| \frac{1 \text{ kPa}}{1000 \text{ Pa}} \right| = \boxed{2.68 \text{ kPa}}$$

5.12 $\Delta p = \rho gh$

$$= \frac{0.800 \text{ g}}{\text{cm}^3} \left| \frac{980 \text{ cm}}{\text{s}^2} \right| \frac{12.7 \text{ cm}}{1000 \text{ g}} \left| \frac{1 \text{ kg}}{\text{m}} \right| \frac{100 \text{ cm}}{1 \text{ kg/ms}^2} \left| \frac{1 \text{ Pa}}{1000 \text{ Pa}} \right|$$

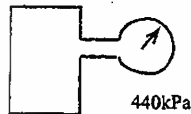
$$= \boxed{0.996 \text{ kPa gage}}$$

Alternate solution:

$$\frac{12.7 \text{ cm}}{2.54 \text{ cm}} \left| \frac{1 \text{ in}}{12 \text{ in}} \right| \frac{0.800}{33.91 \text{ ft H}_2\text{O}} \left| \frac{1 \text{ ft}}{33.91 \text{ ft H}_2\text{O}} \right| \frac{101.3 \text{ kPa}}{1.00} = 1.00$$

5.13 Basis: 750 mm Hg

Atmospheric pressure + gauge pressure = absolute pressure



$$\frac{750 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{101.3 \text{ kPa}}{760 \text{ mm Hg}} \right| = 100 \text{ kPa}$$

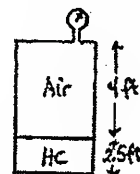
$$\text{absolute pressure} = \frac{440 \text{ kPa}}{540 \text{ kPa}}$$

$$\frac{765 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{101.3 \text{ kPa}}{760 \text{ mm Hg}} \right| = 102 \text{ kPa}$$

$$540 - 102 = \boxed{438 \text{ kPa}}$$

Alternate Solution: $\frac{15 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{101.3 \text{ kPa}}{760 \text{ mm Hg}} \right| \approx 2 \text{ kPa}$ so $440 - 2 = 438 \text{ kPa}$

5.14



(a) Gage pressure most likely (if assume absolute, then don't add barometric pressure below)

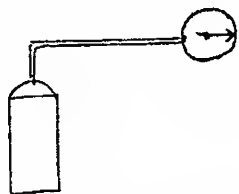
(b) $p = \rho gh$ or use below

Basis: 2.5 ft of HC (ignore pressure exerted by 4 ft of air)

$$\frac{2.5 \text{ ft HC}}{1 \text{ ft HC}} \left| \frac{0.92 \text{ ft H}_2\text{O}}{33.91 \text{ ft HC}} \right| \left| \frac{14.7 \text{ psia}}{33.91 \text{ ft HC}} \right| = 1.00 \text{ psia}$$

$$1.00 \text{ psia} + 20 \text{ psia} + 14.7 \text{ psia (barometer assumed)} = \boxed{35.7 \text{ psia}}$$

5.15 Basis: 1.3 psia



Pressure reads 27.38 in. Hg

Assume the pressure reading is correct, and the barometer reads 101.8 kPa. Convert all measurements to a common set of units, say psi

$$\frac{101.8 \text{ kPa}}{101.3 \text{ kPa}} \left| \frac{14.696 \text{ psia}}{14.696 \text{ psia}} \right. = 14.77 \text{ psia for the barometer}$$

$$\frac{27.38 \text{ in Hg}}{29.92 \text{ in Hg}} \left| \frac{14.696 \text{ psia}}{14.696 \text{ psia}} \right. = 13.45 \text{ psi for the reading}$$

- (a) If the tank is at less than atmospheric (i.e., a vacuum), then $14.77 - 13.45 = 1.32 \text{ psi}$ is a legitimate reading. In other words, the reading is 1.3 psi of vacuum but not 1.3 psia (a reading of $14.77 - 13.45 = 1.3 \text{ psia}$).

- (b) If the tank is greater than atmospheric pressure, then $14.77 + 13.45 = 28.2 \text{ psia}$ is a legitimate reading.

1.3 psia is not correct but the reading is ok.

5.16

Basis: 26.2 in Hg vacuum

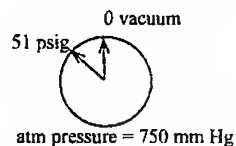
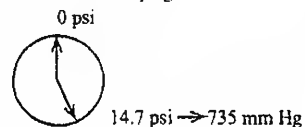
$$p = \frac{(30.4 - 26.2) \text{ in Hg}}{29.92 \text{ in Hg}} \left| \frac{14.7 \text{ psia}}{14.696 \text{ psia}} \right. = \boxed{2.06 \text{ psia}}$$

5.17

$$p = \frac{(29.31 - 3.53) \text{ in Hg}}{29.92 \text{ in Hg}} \left| \frac{760 \text{ mm Hg}}{760 \text{ mm Hg}} \right. = \boxed{655 \text{ mm Hg}}$$

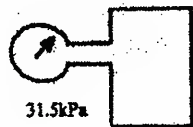
5.18

Vacuum Basis: 51 psig



- 1) Assume the correction to the gauge reading is directly proportional to the gauge reading. The correction is $735/760$ times the gauge reading, and $51(735/760) = 49.3 \text{ psia}$
- 2) An alternate correction is to assume the needed correction is additive. Then the correction is a fixed $(760 - 735) \text{ mmHg}$ reduction, or 25 mm Hg . The second reading should be $51 - 25 \left(\frac{14.7}{760} \right) = 50.5 \text{ psig}$.

5.19



Basis: 31.5 kPa

atmospheric pressure + gauge pressure = absolute pressure

$$98.2 - 31.5 = \boxed{66.7 \text{ kPa absolute}}$$

5.20 Tell him the tank likely will collapse

$$\frac{12 \text{ m H}_2\text{O}}{1 \text{ m}} \left| \frac{3.2808 \text{ ft}}{1 \text{ m}} \right| \frac{1 \text{ atm}}{33.91 \text{ ft H}_2\text{O}} = 1.16 \text{ atm}$$

As the tank drains the pressure inside the tank will become much less than the outside pressure of 1 atm; unless air is let in it will collapse. The valve may not let air in.

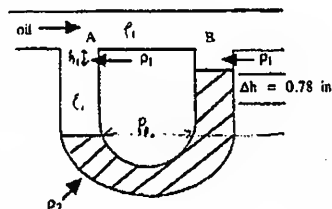
5.21 The pressure of 50 psig is a gauge pressure.

Basis: 50.0 psig

$$\frac{50.0 \text{ psig}}{14.7 \text{ psi}} \left| \frac{33.91 \text{ ft H}_2\text{O}}{1 \text{ ft}} \right| = \boxed{115 \text{ ft. above atmospheric}}$$

No. Insufficient heightAlternate solution can be obtained by applying $\Delta p = \rho \Delta h g$

5.22



$$p_A + \rho_1 g h_1 + \rho_2 g \Delta h = P_D$$

$$p_B + \rho_1 g h_1 + \rho_2 g \Delta h = P_D$$

$$p_A - p_B = \rho_1 g h_1 + \rho_2 g \Delta h - \rho_1 g h_1 - \rho_1 g \Delta h$$

$$= \rho_2 g \Delta h_1 - \rho_1 g \Delta h = g \Delta h (\rho_2 - \rho_1)$$

$$= \frac{9.8 \text{ m}}{\text{s}^2} \left| \frac{0.78 \text{ in}}{3.28 \text{ ft}} \right| \left| \frac{1 \text{ m}}{\text{cm}^2} \right| \left| \frac{13.546 - 0.91 \text{ g}}{1} \right|$$

$$\frac{1 \text{ ft}}{12 \text{ in}} \left| \frac{100 \text{ cm}}{1 \text{ m}} \right|^3 \left| \frac{1 \text{ N}}{\text{m}^2} \right| \left| \frac{1 \text{ Pa}}{101.3 \times 10} \right|$$

$$= \boxed{18.4 \text{ mm Hg}}$$

The pressure at A is higher than the pressure at B.

Alternate solution:

$$\Delta p = \frac{(0.78 \text{ in.})}{13.546} \left| \frac{(13.546 - 0.91)}{29.92 \text{ in. Hg}} \right| 760 \text{ mm Hg} = 18.5 \text{ mm Hg}$$

Solutions Chapter 5

5.23 Basis: 20 in Hg gauge pressure

$$\frac{20 \text{ in. Hg}}{29.92 \text{ in. Hg}} \left| \frac{14.7 \text{ psi}}{1} \right| = 9.83 \text{ psi}$$

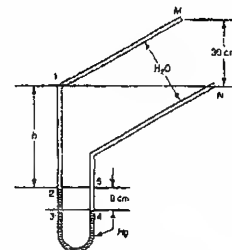
$$\frac{740 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{14.7 \text{ psi}}{1} \right| = 14.3 \text{ psia}$$

$$14.3 - 9.83 = \boxed{4.47}$$

Solutions Chapter 5

5.24 Units for g and ρ must be cm & cm³

$$p = \rho gh$$



$$\text{Pressure at } M = p_M$$

$$\text{Pressure at } 1 = p_M + (30)(\rho_{H_2O})g$$

$$\text{Pressure at } 2 = p_M + (30)(\rho_{H_2O})g + h(\rho_{H_2O})g$$

$$\begin{aligned} \text{Pressure at } 3 &= \text{Pressure at } 4 \\ &= p_M + (30)(\rho_{H_2O})g + h(\rho_{H_2O})g + 6(\rho_{Hg})g \end{aligned}$$

$$\text{Pressure at } 5 = p_M + (30)(\rho_{H_2O})g + h(\rho_{H_2O})g + 6(\rho_{Hg})g - 6(\rho_{H_2O})g$$

$$\begin{aligned} \text{Pressure at } N &= p_M + (30)(\rho_{H_2O})g + h(\rho_{H_2O})g + 6(\rho_{Hg})g - 6(\rho_{H_2O})g \\ &\quad - h(\rho_{H_2O})g = p_N \end{aligned}$$

$$\text{a) } p_N - p_M = [(30 + h - 6 - h)(\rho_{H_2O}) + 6(\rho_{Hg})]g = \boxed{10.3 \text{ kPa}}$$

or

$$24(1) + 6(13.6) = \boxed{105.6 \text{ cm H}_2\text{O}}$$

$$\text{b) } \boxed{p_N > p_M}$$

5.25

Basis: data given

At 2 and 3 the pressure is the same

$$p_A + \rho_{Hg} gh = p_7 + \rho_{oil}g(30) + \rho_{oil}g\left(\frac{h}{2}\right)$$

$p_5 = p_6 = p_7$ so that

$$p_A + \rho_{Hg} gh = p_s + \rho_{oil} g (30) + \rho_{oil} g \left(\frac{h}{2} \right)$$

Also $p_s + p_{oil}g(60) = p_n$

$$\text{Thus: } p_A + \rho_{Hg} gh = p_B - \rho_{oil} g (60) + \rho_{oil} g (30) + \rho_{oil} g \left(\frac{h}{2} \right)$$

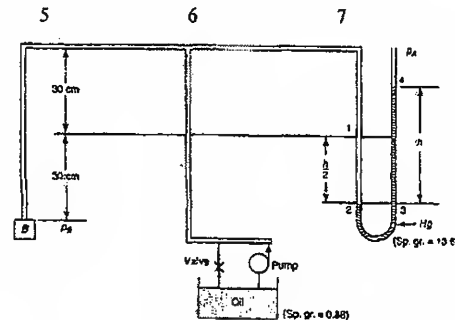
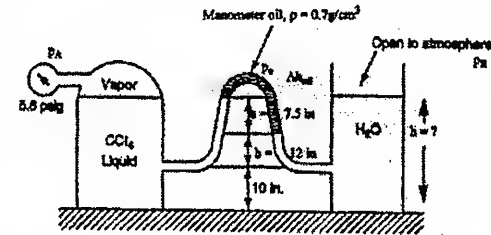


Figure p5.25

$$p_B = p_A + \rho_{Hg} gh + \rho_{oil}g(60) - \rho_{oil}g(30) - \rho_{oil}g\left(\frac{h}{2}\right)$$

$$= p_A + \rho_{Hg} gh + \rho_{oil} g \left[30 - \frac{h}{2} \right]$$

5.26



Basis: Data given in Figure and problem statement

Use $\Delta p = \rho gh$ twice, once for the CCl_4 and oil, and once for the oil and water as systems; $\rho_{\text{CCl}_4} = 1.595 \text{ g/cm}^3$.

$$p_A + \rho_{\text{vap}} g h_{\text{vap}} + \rho_{\text{CCl}_4} g h_{\text{CCl}_4} = p_C + \rho_{\text{oil}} g (\Delta h_{\text{oil}}) + \rho_{\text{CCl}_4} g h_{\text{CCl}_4}$$

$$p_C + \rho_{\text{oil}}g(\Delta h + 7.5) + \rho_{\text{H}_2\text{O}}g(22) = p_B + \rho_{\text{H}_2\text{O}}gh_{\text{H}_2\text{O}}$$

To simplify the two equations, neglect $\rho_{\text{air}}gh_{\text{air}}$. Put all of the terms in the units of inches of water. Note $\rho_1gh_1 = \rho_2gh_2$ for two different fluids exerting the same pressure.

$$p_A = \frac{6.6 \text{ psia}}{14.7 \text{ psia}} \left| \frac{33.91 \text{ ft H}_2\text{O}}{1 \text{ ft}} \right| \frac{12 \text{ in.}}{1 \text{ ft}} = 182.7 \text{ in. H}_2\text{O}$$

$$\rho_{\text{oil}} g h_{\text{oil}} = \frac{7.5 \text{ in. oil}}{1.00 \frac{\text{g H}_2\text{O}}{\text{cm}^3}} \left| \frac{0.7 \frac{\text{g oil}}{\text{cm}^3}}{\text{cm}^3} \right| = 5.3 \text{ in. H}_2\text{O}$$

$\rho_{H_2O} g h_{H_2O}$ in inches of H_2O is 22 in. H_2O

$$h = 182.7 + 5.3 + 22 = \boxed{210 \text{ in. H}_2\text{O}}$$

5.27 The pressure measured by the DP cell is $\Delta p = \rho_{\text{liquid}} g z_{\text{liquid}} + \rho_{\text{vapor}} g z_{\text{vapor}}$.

The pressure is too high by $(\rho_{\text{vapor}} g z_{\text{vapor}})$ and Δp is too high by

$$\left[\left(\frac{\rho_{\text{vapor}} g z_{\text{vapor}}}{\rho_{\text{liquid}} g z_{\text{liquid}}} \right) + 1 \right]$$

5.28 Surface Area

$$\text{Top: } \frac{\pi D^2}{4} = \pi \frac{(8)^2 \text{ m}^2}{4} = 50.3 \text{ m}^2$$

$$\text{Walls: } \pi D h = \pi (8 \text{ m})(10 \text{ m}) = 251.3 \text{ m}^2$$

$$\text{Total area} = 301.6 \text{ m}^2$$

$$\text{Vented area needed} = \frac{0.41 (\text{kPa})^{0.5} (301.6 \text{ m}^2)}{(7.5 \text{ kPa})^{1/2}} = 45.1 \text{ m}^2$$

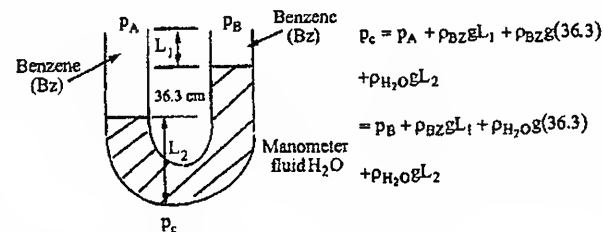
Therefore, the area is not sufficient

$$5.29 \quad p_G + \frac{(420-380) \text{ mm H}_2\text{O}}{13.56 \text{ mm H}_2\text{O}} \left| \frac{1 \text{ mm Hg}}{13.56 \text{ mm H}_2\text{O}} \right| + (380-180) \text{ mm Hg}$$

$$= \frac{12.50 \text{ psia}}{14.7 \text{ psia}} \left| \frac{760 \text{ mm Hg}}{14.7 \text{ psia}} \right| = 646 \text{ mm Hg}$$

$$p_G = 646 - 3 - 200 = \boxed{443 \text{ mm Hg}} \quad (8.57 \text{ psia})$$

5.30



$$p_A - p_B = (\rho_{H_2O} - \rho_{BZ}) g (36.6) =$$

$$\frac{(0.997 - 0.879) \text{ g}}{\text{s}^2} \left| \frac{980 \text{ cm}}{\text{s}^2} \right| \left| \frac{36.3 \text{ cm}}{1 \text{ m}} \right| \left| \frac{100 \text{ cm}}{1 \text{ m}} \right| \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| \left| \frac{1 \text{ N}}{(\text{kg})(\text{m})/\text{s}^2} \right| \left| \frac{1 \text{ kPa}}{10^3 \text{ N/m}^2} \right| =$$

$$\boxed{0.42 \text{ kPa}}$$

5.31 Equate the pressures at the bottom of the two legs of the manometer at the reference plane.

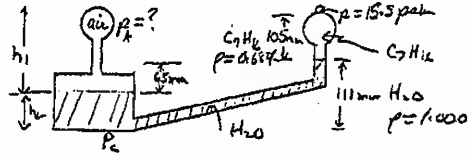
$$\text{Left hand leg pressure } p_{CCl_4} + (2.5 + 1.5)(1590)(9.812) + h_{CCl_4} \times (13600)(9.812) \text{ N/m}^2$$

$$\text{Right hand leg pressure } p_{oil} + (1.5 + h)(800)(9.812) \text{ N/m}^2$$

$$p_{CCl_4} + (2.5 + 1.5)(1590)(9.812) + h(13600)(9.812) = p_{oil} + (1.5 + h)(800)(9.812)$$

$$\text{Manometer Reading} = \boxed{14.6 \text{ cm of Hg}}$$

5.32 Basis: Data shown in Figure



Assume densities are as shown (ignore temperature effects)

$$p_c = p_A + \rho_A g h_1 + \rho_{H_2O} g h_2 = 15.5 \text{ psia} + \rho_{C_7H_{16}} g h_3 + \rho_{H_2O} g h_4$$

↑
ignore as gas density is small

$$p_A = 15.5 \text{ psia} + \rho_{C_7H_{16}} g h_3 + \rho_{H_2O} g (h_4 - h_2)$$

$$= 15.5 + \frac{(62.4)(0.684) \text{ lb}_m}{\text{ft}^3} \left| \frac{\text{g ft}}{\text{s}^2} \right| \frac{10.5 \text{ cm}}{2.54 \text{ cm}} \left| \frac{1 \text{ in}}{12 \text{ in}} \right| \left| \frac{1 \text{ ft}}{12 \text{ in}} \right|$$

$$\times \frac{1 \text{ lb}_r}{32.2 \frac{(\text{lb}_m)(\text{ft})}{\text{s}^2}} \left(\frac{1 \text{ ft}}{12 \text{ in}} \right)^2 + \frac{62.4 \text{ lb}_m}{\text{ft}^3} \left| \frac{\text{g ft}}{\text{s}^2} \right| \frac{6.3 \text{ cm}}{2.54 \text{ cm}} \left| \frac{1 \text{ in}}{12 \text{ in}} \right|$$

$$\times \frac{1 \text{ in}}{2.54 \text{ cm}} \left| \frac{1 \text{ ft}}{12 \text{ in}} \right| \frac{1 \text{ lb}_r}{32.2 \frac{(\text{lb}_m)(\text{ft})}{\text{s}^2}} \left(\frac{1 \text{ ft}}{12 \text{ in}} \right)^2 = 15.69 \text{ psia}$$

$$15.69 - 14.69 = \boxed{1.0 \text{ psig}}$$

5.33 Basis: 3.1 cm fluid

$$\frac{3.1 \text{ cm fluid}}{1.00 \text{ cm fluid}} \left| \frac{(1.30 - 1.00) \text{ cm H}_2\text{O}}{2.54 \text{ cm}} \right| \left| \frac{1 \text{ in}}{12 \text{ in}} \right| \left| \frac{1 \text{ ft}}{33.91 \text{ ft H}_2\text{O}} \right| \left| \frac{101.3 \text{ kPa}}{1 \text{ atm}} \right| = \boxed{0.091 \text{ kPa}}$$

Alternate solution:

$$p_A + \rho_w g h_1 = p_B + \rho_w g h_2 + \rho_{\text{fluid}} g \Delta H$$

$$p_A - p_B = \rho_w g h_2 + \rho_{\text{fluid}} g \Delta H - \rho_w g h_1 - \rho_w g \Delta H$$

$$= \rho_{\text{fluid}} g \Delta H - \rho_w g \Delta H = g \Delta H (\rho_{\text{fluid}} - \rho_w)$$

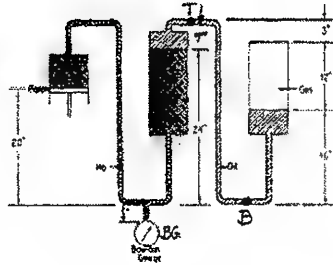


$$= \left(\frac{1.30 \text{ g} - 1.00 \text{ g}}{\text{cm}^3} \right) \left| \frac{980 \text{ cm}}{\text{s}^2} \right| \left| \frac{3.1 \text{ cm fluid}}{10^3 \text{ g}} \right| \left| \frac{1 \text{ kg}}{10^3 \text{ g}} \right| \left| \frac{100 \text{ cm}}{1 \text{ m}} \right| \left| \frac{1 \text{ Pa}(\text{s}^2)(\text{m})}{1 \text{ N}} \right|$$

$$= 0.091 \text{ kPa}$$

Solutions Chapter 5

5.34



The pressure at BG is

$$33.1 \text{ psig} + \frac{720 \text{ mm Hg}}{760 \text{ mm Hg}} \cdot 14.7 \text{ psia} = 47.0 \text{ psi}$$

$$\frac{47.0 \text{ psia}}{14.7 \text{ psia}} \cdot 101.3 \text{ kPa} = 324 \text{ kPa}$$

$$p_T = 7 \text{ in. oil} + 27 \text{ in. Hg}$$

$$p_T = 31 \text{ in. oil} = p_B$$

$$p_{G_{85}} + 16 \text{ in. oil} = p_B$$

$$p_{G_{85}} = 324 \text{ kPa} - 7 \text{ in. oil} - 27 \text{ in. Hg} + 31 \text{ in. oil} - 16 \text{ in. oil}$$

$$= 324 \text{ kPa} + 8 \text{ in. oil} - 27 \text{ in. Hg}$$

Convert in. oil and in. Hg to kPa

$$p_{G_{85}} = 324 + 1.59 - 91 = \boxed{235 \text{ kPa}}$$

Solutions Chapter 6

6.1

Basis: 1 minute

Accumulation (kg)	In (kg)	Out (kg)
-------------------	---------	----------

$$m_{\text{final}} - 0 = 300 + 100 - 380$$

$$n_{\text{final}} = 20 \text{ kg}$$

$$\frac{20 \text{ kg}}{\text{min}} \left| \frac{60 \text{ min}}{1 \text{ hr}} \right| = \boxed{1200 \text{ kg}}$$

6.2

Basis: 600 kg solution

Accumulation (kg)	In (kg)	Out (kg)
-------------------	---------	----------

$$n_{\text{final}} - 0 = 100 + 500 - 300$$

$n_{\text{final}} = 300 \text{ kg}$ if no water evaporates in which case less than 300 kg would remain

6.3

(c) $\boxed{27.0 \text{ g}}$

6.4

Basis: 1 hr

Overall material balance (kg): $13,500 + 26,300 \stackrel{?}{=} 39,800$

Solutions Chapter 6

Yes. The balance is satisfied

NaCl balance: $0.25 (13,500) + 0.05 (26,300) \stackrel{?}{=} 0.118 (39,800)$

$$4690 \cong 4696$$

The balance is closely satisfied but not exactly.

The closure is good for industrial practice.

6.5

Based on the process measurements, there are 5,000 lb/h more flow for the process leaving the heat exchanger than the feed rate to the heat exchanger; therefore, the material balance for the process fluid does not close. The reason for this discrepancy could be faulty flow sensor readings or possibly a leak of the condensate or steam into the process stream.

6.6

Basis: 1 hour

The overall material balance is

In (lb)		Out (lb)
106,000	$\stackrel{?}{=}$	74,000 + 34,000 = 108,000

The error in the overall material balance is 2000 lb/h or 1.9%; therefore, the overall material balance is within the expected error for industrial flow sensors.

Propylene balance: $0.7 \times 106,000 \stackrel{?}{=} (0.997) (74,000) + (0.1) (34,000)$
 $74,200 \stackrel{?}{=} 73,778 + 3,400 = 77,178 \text{ (3.8\% error)}$

Propane balance: $0.4 \times 106,000 \stackrel{?}{=} (0.003) (74,000) + (0.9) (34,000)$
 $31,800 \stackrel{?}{=} 222 + 30,600 = 30,622 \text{ (3.8\% error)}$

Note that the relative error for the component balances are twice as large as the relative error for the overall material balance, indicating that there is additional error in the composition measurements used for the component balances.

Solutions Chapter 6

6.7

Basis: Data shown on flowsheet units are MTA

<u>In</u>	<u>Out</u>
2.5×10^6	404×10^3
	228×10^3
	152×10^3
	101×10^3
	67×10^3
	36×10^3
	100×10^3
	1190×10^3
	$2,278 \times 10^3$

mass in does not equal to mass out.

Reasons:

- (1) Some of the material was burned as fuel
- (2) Some of the material formed gases that were exhausted to atmosphere (such as H_2O , CO_2).
- (3) errors in measurement.
- (4) Some process streams are not shown.

6.8

In = 250,000 ton/yr. Out = 244,500 ton/yr.

<u>In (ton/yr)</u>	<u>Out (ton/yr)</u>
250,000	Combustibles 3,800
	Combustibles 39,500
	Polyethylene 30,000
	Polystyrene 5,000
	PVC 40,000

Solutions Chapter 6

Acrylonitrile	20,000
DB	8,000
Phenol	10,000
Acetone	5,750
Rubber	10,000
LPG	24,000
Aromatics	<u>48,000</u>
Total	244,050

Balance is not exact but very good for an operating plant.

6.9

Basis: 1 week

in (tons) = $920 + 0.6 = 920.6$

out (tons) = $3.8 + 620 + 0.01 + 0.01 + 0.08 + 1.1 + 275 + 20 = 920$

Yes

6.10

Boundary: Around both pumps and include the soil at the end of the pipes.

It's an open system.

It's at steady-state except at startup (note system boundary limits fluid), or if fluid enters, unsteady state.

6.11 Either open (flow) or closed (batch) is acceptable if explanation is given

- (1) flow – material comes in and out continuously over a suitably long period of time
- (2) batch – material is injected into the system, and then in a short period of time, a reaction occurs with the system valves closed.

Solutions Chapter 6

6.12

- a) closed
- b) open
- c) open
- d) closed

6.13

The system is the radiator.

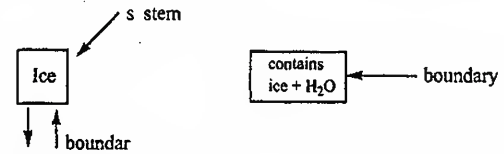
	<u>Open System</u>	<u>Closed System</u>	<u>Steady-State</u>	<u>Unsteady State</u>
a)	X			X
b)	X			X
c)	X (Before filling)	X (After filling)	X (After filling)	X (Before Filling)
d)		X	X	

6.14

- (a) open if you have to replace water, and water evaporates; otherwise closed
- (b) open

Solutions Chapter 6

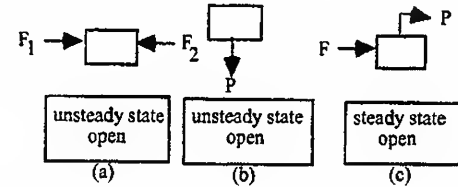
6.15



(c) Unsteady state for any assumptions

- b) assume water (melted ice) leaves the system { open
- a) flow
- b) assume water stays in sytem because the ice and water { closed
- a) remain on melting batch

6.16



6.17 If the overall flows in and out over a time period for several batches are considered, and the local batches ignore, the process can be treated as continuous.

- 6.18 (a) water and air.
 (b) Insulation, air and what is in the atmosphere.
 (c) Yes (cold water in, hot water out)
 (d) Yes

6.19 If a reaction occurs, some of the entering moles will be used up, and new ones produced that exit but did not enter.

6.20 The density of the crystalline silicon in the cylinder is 2.4 g/cm^3 .

Basis: 62 kg silicon

The system is the melt, and there is no generation or consumption. Let Δm_i be the accumulation.

$$\frac{\text{Accumulation}}{\Delta m_i} = \frac{\text{Input}}{0} - \frac{\text{Output}}{0.5(62 \text{ kg})}$$

$$\Delta m_i = -31 \text{ kg}$$

Let t be the time in minutes to remove one-half of the silicon

$$\frac{2.4 \text{ g}}{\text{cm}^3} \left| \frac{\pi(17.5 \text{ cm})^2}{4} \right| \frac{0.3 \text{ cm}}{\text{min}} \left| \frac{t \text{ min}}{\text{min}} \right| = \frac{1}{2} (62,000 \text{ g})$$

$$t = 179 \text{ min}$$

6.21

Basis: 100 kg wet sludge

The system is the thickener (an open system). No accumulation, generation, or consumption occur. The total mass balance is

$$\frac{\text{In}}{100 \text{ kg}} = \frac{\text{Out}}{70 \text{ kg} + \text{kg of water}}$$

Consequently, the water amounts to $\boxed{30 \text{ kg}}$.

6.22

	(a)	(b)	(c)	(d)	(e)	(f)	(g)
1.				x		x	
2.	x				x		
3.	x					x	
4.	Depends on the time period considered						
5.		x				x	
6.			x	x			x
7.			x			x	

6.23

If the overall flows in and out over a time period for several batches are considered, and the local batches ignore, the process can be treated as continuous.

6.24

It depends on the process of interest – no fixed answer can be given.

Solutions Chapter 7

7.1

Four balances are possible, 3 component plus 1 total.

$$0.10F_1 + 0.50F_2 + 0.20F_3 = 0.35P$$

$$0.20F_1 + 0F_2 + 0.30F_3 = 0.10P$$

$$0.70F_1 + 0.50F_2 + 0.50F_3 = 0.55P$$

$$\text{Total balance } F_1 + F_2 + F_3 = P$$

Only 3 of the equations are independent.

7.2

If you specify F, P, W, you can calculate all of the stream variables.

- Unknown: three stream values F, P, W (plus two compositions if you take into account all of the variables).
- The two known compositions are not given but may be calculated from $\Sigma x_i = 1$,
- Two components exist, hence two independent material balances can be written. The problem cannot be solved unless one stream value is specified.

7.3

- No. The equations have no solution – they are parallel lines.

The rank of the coefficient matrix is only 1 because the

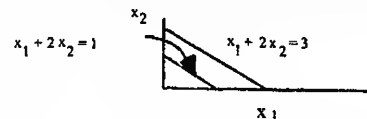
$$\det \begin{bmatrix} 1 & 2 \\ 1 & 2 \end{bmatrix} = 0$$

The rank of the augmented matrix is 2

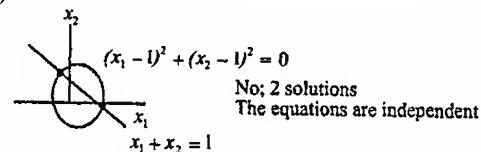
Solutions Chapter 7

Largest non zero det. of $\begin{bmatrix} 1 & 2 & 1 \\ 1 & 2 & 3 \end{bmatrix}$ is of order 2

Thus, although the 2 equations are independent and the number of variables is 2 (the necessary conditions), the sufficient conditions are not met.



(b)



Two solutions exist as can be seen from the plot hence no unique solution exists.

- The number of independent equations is just 3. The number of unknown quantities is 3, hence a unique solution is possible.

Solutions Chapter 7

7.5

[No for both]

a) $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 2 & 3 \\ 3 & 5 & 7 \end{bmatrix}$ rank of coefficient matrix is 2.
rank of augmented matrix is 2.

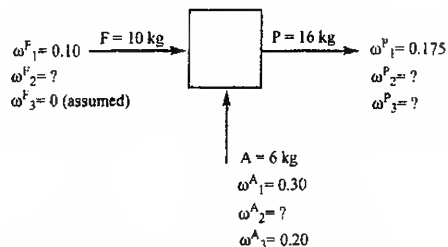
$r = 2, n = 3$ multiple solutions exist

b) $\begin{bmatrix} 1 & 0 & 1 \\ 5 & 4 & 9 \\ 2 & 4 & 6 \end{bmatrix}$ 3d column is sum of 1st two columns, so rank is 2.
rank of augmented matrix is 2, also.

$r = 2, n = 3$ multiple solutions exist

7.6 (a) F; (b) F; (c) F (the maximum can be more than the number of independent equations).

7.7



Unknowns (4): $\omega_2^F, \omega_2^A, \omega_2^P, \omega_3^P$

Equations:

Solutions Chapter 7

Mass balances:

(1): $F(0.10) + A(0.30) = P(0.175)$
 or $10(0.10) + 6(0.30) = 16(0.175)$ redundant
 (2): $F(\omega_2^F) + A(\omega_2^A) = P(\omega_2^P)$
 or $10(\omega_2^F) + 6(\omega_2^A) = 16(\omega_2^P)$
 (3): $F(0) + A(0.20) = P(\omega_3^P)$
 or $10(0) + 6(0.20) = 16(\omega_3^P)$

$\omega_2^F, \omega_2^A, \omega_2^P, \omega_3^P$

$\begin{bmatrix} 10 & 6 & -16 & 0 \\ 0 & 0 & -16 & 16 \end{bmatrix}$ coeff. matrix

Two independent material balances exist (the rank of the coefficient matrix is 2). In addition three sum of mole fraction equations exist. The total number of equations is 5, hence the degrees of freedom = -1. The problem is overspecified, and will require a least squares solution.

7.8

Examine the row of C_3H_8 . None of the concentrations are greater than the desired 50% so 50% is not achievable by any combination of A, B, or C. Or look at the CH_4 row.

7.9

Basis: D = 100 lb

Coefficient matrix is

	A	B	C	D
	x_1	x_2	x_3	
5.0	0	0	:	1.4
90.0	10.0	0	:	31.2
5.0	85.0	8.0	:	53.4
0	5.0	80.0	:	12.6
0	0	12.0	:	14

continued

Solutions Chapter 7

No unique solution exists with 5 equations and 4 variables. A least squares solution could be determined, or the 4 equations with the most accurate data solved.

The rank of the coefficient matrix is 3

The rank of the augmented matrix is 4

Hence no unique solution exists

7.10

You can see by inspection that no combination of tanks 1, 2 and 3 will give a mole fraction of 0.52 for the mixture.

Basis: 2.50 mol of tank 4

Let x_i = be the total moles of tank i

The balances are

$$\begin{aligned} 0.23x_1 + 0.20x_2 + 0.54x_3 &= 0.25(2.5) = 0.625 \\ 0.36x_1 + 0.33x_2 + 0.27x_3 &= 0.23(2.5) = 0.575 \\ 0.41x_1 + 0.47x_2 + 0.19x_3 &= 0.52(2.5) = 1.300 \end{aligned}$$

The coefficient matrix has a rank of 3 as does the augmented matrix so the set of equations has a solution. However, the solution is

$$\begin{aligned} x_1 &= -4.00 \\ x_2 &= 6.36 \\ x_3 &= -0.327 \end{aligned}$$

The values of x_1 and x_3 are not physically realizable!

Solutions Chapter 7

7.11 Number of unknowns:

F, W, P and 9 compositions: 12

Equations

Specifications: $x_{cr}^w = 0$ 1

Sum of mole fractions = 1 3

Material balances (3 species) 3 7

Degrees of freedom = 5

You can make any set of measurements that results in independent equations (assuming equal accuracy). For example, you cannot use all the flows, or all the compositions in one stream, as the resulting set of material balances will not consist of 5 independent balances, but a lesser number.

7.12

The inerts are treated as a compound.

Unknowns: 5 compounds $\times$ 5 streams plus 5 streams = 30

Equations: Specifications:

Concentrations not shown in diagram assumed to be zero 8

Concentrations with % given 7

$E = 11$ kg 1

Material balances: 5 5

Implicit equations ($\Sigma \omega_i = 1$) 5 26

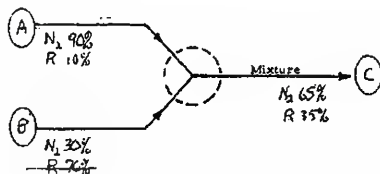
a. Degrees of freedom (additional specifications) = 4

You must make 4 measurements that result in independent equations

b. No.

7.13

a.

b. The remaining gas is 100% minus the N_2 , and was put on the figure as R.

c. Basis: 100 mol A

d. Unknowns: A, B, C

Equations: N_2 and R material balances

Basis = A = 100 mol

Note: You could treat the values of R as unknowns in each stream, and then there would be 3 more unknowns and 3 more independent equations ($\sum x_i = 1$ or $\sum m_i = \text{total mass flow}_i$)

e.&f. $N_2: 100(0.90) + B(0.30) = C(0.65)$

$R: 100(0.10) + B(0.70) = C(0.35)$

Total: $100 + B = C$

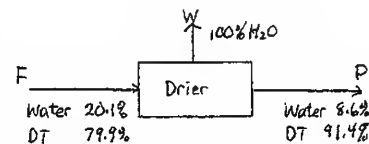
Two of the above equations are independent

g. Solution: $B = 71.4 \text{ mol}$ $C = 171.4 \text{ mol}$

$$\frac{A}{B} = \frac{100}{71.4} = \boxed{1.40}$$

7.14

a.



DT = dry timber

b. The DT is the balance of each stream.

c. Basis: $F = 100 \text{ kg}$ d. Unknowns: F, W, P OR F, W, P, DT^F , DT^W , DT^P , H_2O^F , H_2O^P , H_2O^W Equations:Basis: $F = 100 \text{ kg}$ Material Balances: Water, DT
(total); 2 independentEquations: $F = 100 \text{ kg}$ Material Balances: Water, DT,
(total); 2 independent

Specifications: 3 for water

Implicit equations: 3 of $\sum \omega_i = 1$

Degrees of freedom = 0

Degrees of freedom = 0

e.&f. Introducing the specifications and basis into the material balances:

Water: $(0.201)100 = (1)W + (0.086)P$

DT: $(0.80)100 = 0 + (0.914)P$ a tie element

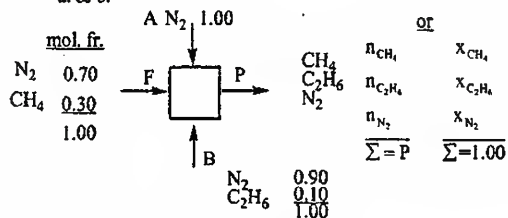
Total: $100 = W + P$

g. $W = 12.5 \text{ kg}$ $P = 87.5 \text{ kg}$

$$\frac{W}{F} = \frac{12.5 \text{ kg}}{100 \text{ kg}} = \boxed{0.125 \text{ kg/kg}}$$

7.15

a. & b.



c. Basis: B = 100 mol

d. Unknowns:

Assume all of the variables except those that are specified as zero are included in the analysis.

	<u>stream variable</u>	<u>component variables</u>
F	1	2
A	1	1
P	1	3
B	1	2
	4	8
		= 12

Equations:

Basis:	1
Material balances: N_2, CH_4, C_2H_6	3
Specified ratio: $n_{CH_4}/n_{C_2H_6} = 1.3$	1
Specified values of n: $2 + 1 + 0 + 2 =$	5
Implicit equations ($\Sigma x_i = 1$ in P)	1
(Note: the implicit equations of streams F, A, and B are redundant with the specifications)	
Total	11
Degrees of freedom =	1

More information is needed to solve the problem uniquely.

7.16

Here are some possibilities. Consult the tables at the end of the Chapter for more suggestions.

1. Rephrase the problem to make sure you understand it?
2. Draw a simple diagram of what was happening?
3. Think about what was going into the tank and what was coming out?
4. Imagine yourself inside the tank, and ask what was going on around you?
5. Ask whether there were any physical laws to consider (such as conservation of matter or energy)?
6. Try to imagine the answer as a number, graph, table, or whatever?
7. Try to identify essential variables?
8. Choose a notation?
9. Look for a ready-made formula for the answer?
10. Look for simplifying assumptions?
11. Try to find an easier version of the problem?
12. Look for bounds (simple models that would definitely underestimate or overestimate the answer)?

Solutions Chapter 8

8.1

Basis: 100 kg cucumbers

P - 100 = evaporated

	Initial	Final (P)	Evaporated
Cucumber	1 kg	2%	-
Water	99 kg	98%	100%
	100 kg	100%	100%

Cucumber balance: $0.02P - 0.01(100) = 0$

P = 50 kg Answer is: Yes

8.2

Initial	Final
plant 5 ppm	Plant 755 ppm
soil 6 ppm	Soil 5 ppm

Final - Initial

Final - Initial

Arsenic balance: $S(5) - S(6) =$

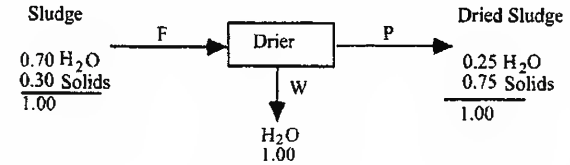
$P(755) - P(5)$

$$750P = S \text{ or } \frac{S}{P} = 750$$

Solutions Chapter 8

8.3 Step 5: Basis is 1 ton (2000 lb) sludge

Steps 1, 2, 3, 4:



Steps 6 and 7:

Basis: 2000 lb F

Balances: H₂O
Solids

Unknowns: P, W

Steps 8 and 9:

Total: $2000 = P + W$

Solids: $2000(0.30) = P(0.75)$

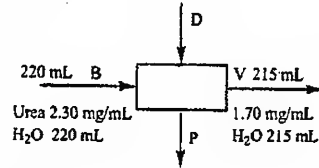
$P = 800 \text{ lb}$

$W = 2000 - 800 = 1200 \text{ lb}$

Solutions Chapter 8

8.4 Step 5: Basis: 1 min

Steps 2, 3, 4:



Steps 6 and 7: Unknowns: m^F_{urea} and $m^F_{\text{H}_2\text{O}}$ with two equations: urea and H_2O .
Degrees of freedom = 0.

Steps 8 and 9:

(a) H_2O balance: $220 \text{ mL} - 215 \text{ mL} = \boxed{5 \text{ mL}}$

Urea balance: $\frac{2.30 \text{ mg}}{\text{mL}} \left| \frac{220 \text{ mL}}{\text{mL}} \right| - \frac{1.70 \text{ mg}}{\text{mL}} \left| \frac{215 \text{ mL}}{\text{mL}} \right| = \boxed{141 \text{ mg}}$

(b) Dialysate: $1500 + 5 = 1505 \text{ mL}$

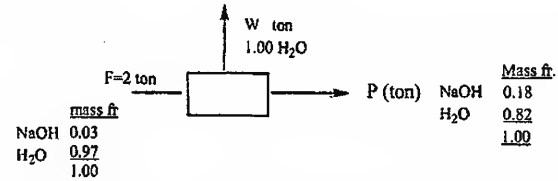
Urea: 141 mg

Concentration: $141/1505 = \boxed{0.0934 \text{ mg/mL}}$

Solutions Chapter 8

8.5 Step 5: Basis: 1 day

Steps 2, 3, 4:



Step 6: Unknowns, 2: P, W

Step 7: Balances 2: NaOH, H_2O , total (2 of the 3)

Steps 8 & 9:

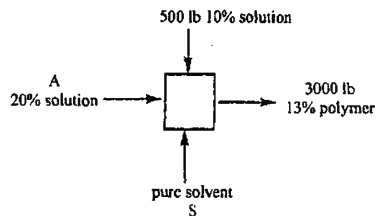
Total: $2 = W + P$
NaOH: $2(.03) = P(.18)$

$P = 1/3 \text{ ton}$
(666 lb)

$W = 1 \frac{2}{3} \text{ ton}$
(3334 lb)

Solutions Chapter 8

8.6 Steps 2, 3, 4:



Step 5:

Basis: 3000 lb of final product

Steps 6 and 7: Unknowns: A and S; balances: total and polymer

Steps 8 and 9:

Total wt $A + S + 500 = 3000$

$A + S = 2500$

Polymer $0.2A + 50 = 390$

$A = 5(340) = \boxed{1700}$

$S = 2500 - 1700 = \boxed{800}$

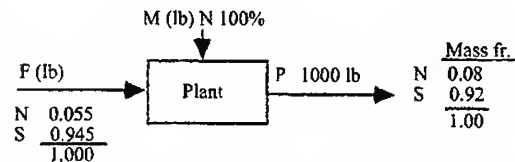
Solutions Chapter 8

8.7

Steps 1, 2, 3 and 4:

N = nitrocellulose
S = solvent

Treat the problem as a steady state flow problem, or as an unsteady state batch system. As a flow system:



Step 5: Basis: 1000 lb P

Steps 6 and 7: Two unknowns, F and M. Two balances can be made, N and S.

Steps 8 and 9:

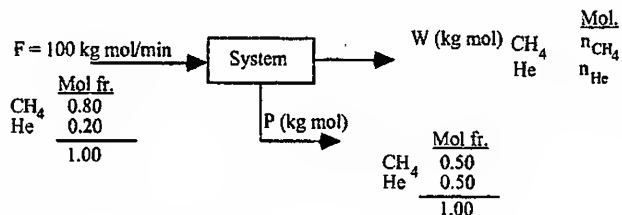
Solve to get

N:	$F(0.055) + M(1.00) = 1000(0.008)$	}	$F = 973.5 \text{ lb}$
S:	$F(9.045) + M(0) = 1000(0.92)$	}	$M = 26.5 \text{ lb}$
			$P = 1000.0 \text{ lb}$

Solutions Chapter 8

8.8

Steps 1, 2, 3 and 4:

Step 5: Basis 1 min $\rightarrow$ 100 kg mol F

Step 4: To get P, calculate first the average mol. wt. of F and P, or transform the mole fractions to mass fractions.

Step 5: Basis: 1.00 mol F

	<u>Mol</u>	<u>MW</u>	<u>kg</u>
CH ₄	0.80	16.03	12.8
He	0.20	4	0.8
	1.00		13.6

Basis: 1.00 mol P

	<u>Mol</u>	<u>MW</u>	<u>kg</u>
CH ₄	0.50	16.03	8.01
He	0.50	4	2.0
	1.00		10.01

100 kg mol F	13.6 kg F	0.20 kg P	1 kg mol P
	1.00 kg mol F	1 kg F	10.01 kg P

(continued)

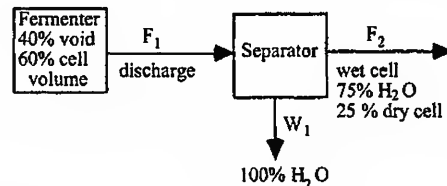
Solutions Chapter 8

P = 27.2 kg mol

Steps 6, 7, 8 and 9:

		<u>In W</u>	<u>Mol.fr.</u>
$100(0.80) = 27.2(0.50) + n_{CH_4}$	n_{CH_4}	66.4	0.912
$100(0.20) = 27.2(0.50) + n_{He}$	n_{He}	6.4	0.088
		72.8	1.00

8.9

Basis: 1000 cm³ F₁

$$\text{Dry cells} = \frac{1000 \text{ cm}^3 \text{ in fermenter}}{100 \text{ cm}^3 \text{ in fermenter}} \times \frac{60 \text{ cm}^3 \text{ cell}}{1 \text{ cm}^3 \text{ cell}} \times \frac{1.1 \text{ g cell}}{1 \text{ cm}^3 \text{ cell}} \times \frac{25 \text{ g solids}}{100 \text{ g cell}}$$

$$= 16.5 \text{ g Dry cell} / 1000 \text{ cm}^3 \text{ in fermenter}$$

Solutions Chapter 8

8.10

a. Basis: 1 kg mole of mixture

Three components exist: $(\text{CH}_4)_x$, $(\text{C}_2\text{H}_6)_x$, $(\text{C}_3\text{H}_8)_x$

Let A, B, C respectively represent kg mol of each mixture; these are the unknowns.

$$\begin{aligned} \text{Equations:} \quad & 0.25A + 0.35B + 0.55C = 0.30 \quad (\text{CH}_4)_x \text{ balance} \\ & 0.35A + 0.20B + 0.40C = 0.30 \quad (\text{C}_2\text{H}_6)_x \text{ balance} \\ & 0.40A + 0.45B + 0.05C = 0.40 \quad (\text{C}_3\text{H}_8)_x \text{ balance} \end{aligned}$$

There is a unique solution to the set of equations (in kg mol)

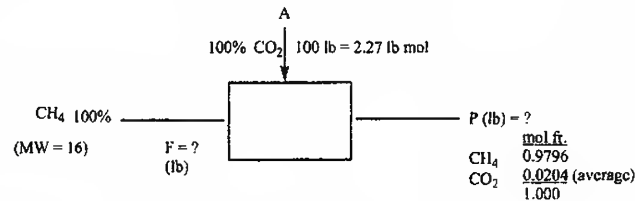
The solution is $A = 0.600$ $B = 0.350$ $C = 0.05$

b. It is proposed to prepare the final mixture by blending four different compounds (A, B, C, D); there will still be three equations, but now there will be four unknowns. Since the rank is now less than n , there will be an infinite number of possible blends of the four mixtures. Not required: (An optimization of a revenue function subject to the equations is needed.)

Solutions Chapter 8

8.11

a.



Steps 2, 3, 4: $\frac{100 \text{ lb}}{44 \text{ lb}} \times \frac{1 \text{ lb mol}}{1} = 2.27 \text{ lb mol}$

Step 5: Basis 1 min

Step 6: Unknowns: F, P

Step 7: Balances: CH₄, CO₂

Steps 8 and 9: Balances in moles

$$\text{CH}_4: F(1.00) + A(0) = P(0.9796)$$

$$\text{CO}_2: F(0) + 2.27 = P(0.0204) \quad P = 111.41 \text{ lb mol}$$

$$F = \frac{111.27 \text{ lb mol}}{1 \text{ lb mol P}} \times \frac{0.9796 \text{ lb mol CH}_4}{1 \text{ lb mol CH}_4} \times \frac{16 \text{ lb CH}_4}{1 \text{ lb mol CH}_4} = 1746 \text{ lb/min} \quad (a)$$

b. Redo the problem with a new composition for F:

$$\begin{array}{ll} \text{CH}_4 & 0.99 \\ \text{CO}_2 & 0.01 \\ & 1.00 \end{array}$$

(continued)

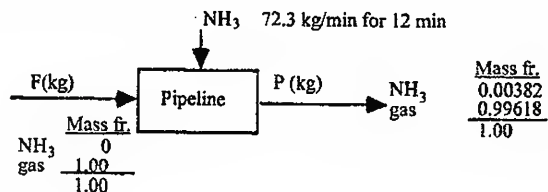
Solutions Chapter 8

$$\left. \begin{array}{l} \text{CH}_4: F(0.99) + A(0) = P(0.9796) \\ \text{CO}_2: F(0.01) + 2.72 = P(0.0204) \end{array} \right\} F = 3520 \text{ lb/min}$$

$$\text{error } \frac{3520-1744}{3520} 100 = \boxed{50\%} \quad (\text{b})$$

8.12

Steps 1, 2, 3, and 4:



Step 5: Basis: 1 min

Steps 6 and 7: Two unknown, F and P. Two balances can be made, NH_3 and gas. You can use the total balance as a substitute.

Steps 8 and 9:

$$\text{Total} \quad F + 72.3 = P$$

$$\text{NH}_3 \quad F(0) + 72.3 = P(0.00382)$$

$$\boxed{P = 18,900 \text{ kg/min}}$$

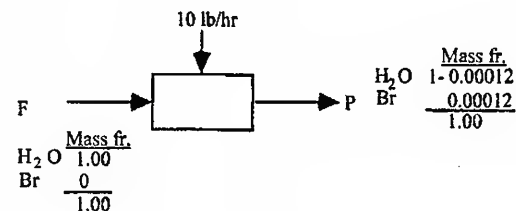
$$\boxed{F = 18,900 \text{ kg/min or } 1.14 \times 10^6 \text{ kg/hr}}$$

Step 10: Check using the gas balance

Solutions Chapter 8

8.13

Steps 1, 2, 3, and 4:



Step 5: Basis: 1 hr

Step 6: Unknowns: F, P

Step 7: Balances: H_2O , Br

Steps 8 and 9:

$$\text{Total:} \quad F + 10 = P$$

$$\text{Br:} \quad F(0) + 10 = P(0.00012) \quad ; \quad P = 8.33 \times 10^4 \text{ lb/hr}$$

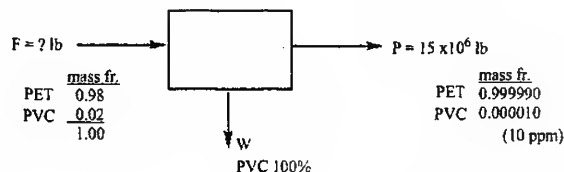
$$\text{H}_2\text{O:} \quad F(1.00) + 0 = P(1-0.00012)$$

$$\boxed{F = 8.33 \times 10^4 - 10 = 8.33 \times 10^4 \text{ lb/hr}}$$

Solutions Chapter 8

8.14 Step 5: Basis: 1 year

Steps 2, 3, 4:



Steps 6 and 7:

Two unknowns: F, W Two balances: PET, PVC

Steps 8 and 9:

$$\text{PET balance: } F(.98) = P(.999990) \approx 15 \times 10^6$$

$$\text{PVC balance: } F(.02) = W(1.00) + P(0.000010) \\ = W + (15 \times 10^6)(10^{-5})$$

Total balance could be used in lieu of one of the above

$$F = 15 \times 10^6 + W$$

$$\text{From PET: } F \approx 15.3 \times 10^6 \text{ lb}$$

$$W = (15.3 \times 10^6)(0.02) - 15 \times 10^6(10^{-5}) = 0.31 \times 10^6 \text{ lb}$$

Solutions Chapter 8

8.15

Basis: 300 g initial solution

MW $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ is 322.2

In	g	MW	g mol	Out	g	g mol
Na_2SO_4	100	142.05	0.704	$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	100	0.310
H_2O	200	18.016	11.10			

Material balances in g mol (in = out):

$$\text{Na}_2\text{SO}_4: 0.704 = 0.310 + n_{\text{Na}_2\text{SO}_4} \quad n_{\text{Na}_2\text{SO}_4} = 0.394 \quad 55.97 \quad 28$$

$$\text{H}_2\text{O}: 11.10 = 0.310(10) + n_{\text{H}_2\text{O}} \quad n_{\text{H}_2\text{O}} = 8.0 \quad 144.1 \quad 72$$

$$\text{Total} \quad 8.394 \quad 200.07 \quad 100$$

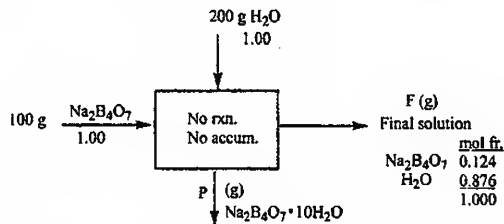
Mother liquor: Na_2SO_4 is 28% and H_2O is 72%

$$(b) \quad \frac{100 \text{ g crystals}}{300 \text{ g solution}} \bigg| \frac{100 \text{ g solution}}{300 \text{ g solution}} = 33.3 \text{ g crystals/100 g initial soln.}$$

Solutions Chapter 8

8.16 Assume steady state flow problem (alternate is unsteady state batch problem).

Steps 1-4:



Calculate composition of P: Basis: 100 mol $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$

	mol	MW	g	mol fr.
$\text{Na}_2\text{B}_4\text{O}_7$	1	201.27	201.27	0.528
H_2O	10	18	180.0	0.472
			381.27	1.00

Step 5: Basis: 200 g H_2O + 100 g $\text{Na}_2\text{B}_4\text{O}_7$

Step 6: Unknowns: F, B

Step 7: balances: $\text{Na}_2\text{B}_4\text{O}_7$, H_2O

Step 8: $\left. \begin{array}{l} \text{Na}_2\text{B}_4\text{O}_7: 100 = P(0.528) + F(0.124) \\ \text{H}_2\text{O}: 200 = P(0.472) + F(0.876) \end{array} \right\} 2 \text{ indept.}$

Total: $100 + 200 = P + F$

Step 9: Use H_2O and Total to get $P = 155.5\text{g}$ and $F = 144.5\text{g}$

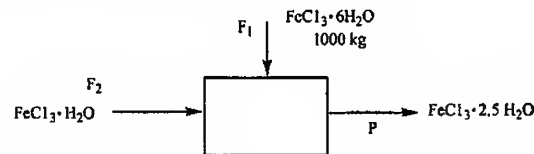
$$\text{ratio: } \frac{155.5}{300}(100) = \boxed{51.8 \text{ g Na}_2\text{B}_4\text{O}_7 / 100 \text{ g H}_2\text{O}}$$

Solutions Chapter 8

Step 10: Check use $\text{Na}_2\text{B}_4\text{O}_7$
 $100.0 = 100.0$ ok

8.17 Assume the process is a steady state one without reactions.

Steps 1, 2, 3, 4:



MW	FeCl_3	162.22
	$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	270.32
	$\text{FeCl}_3 \cdot \text{H}_2\text{O}$	180.24
	$\text{FeCl}_3 \cdot 2.5 \text{H}_2\text{O}$	207.26
	H_2O	18.02

Calculate the compositions for just one iron compound. FeCl_3 is the simplest to use.

For F_1 : Basis: 1 kg mol

For F_2 : Basis: 1 kg mol

$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$

$\text{FeCl}_3 \cdot 1\text{H}_2\text{O}$

	kg mol	MW	kg		kg mol	MW	kg
FeCl_3	1	162.22	162.22	FeCl_3	1	162.22	162.22
H_2O	6	18.03	108.18	H_2O	1	18.03	18.03
			270.40				180.25

For P Basis: 1 kg mol

	kg mol	MW	kg
FeCl_3	1	162.22	162.22
H_2O	2.5	18.03	45.08
			207.30

(continued)

Solutions Chapter 8

Step 5: Basis: 1000 kg $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$

Step 6: Unknowns P, F

Step 7, 8, 9: Balances (kg)

$$\text{FeCl}_3: 1000 \left(\frac{162.22}{270.40} \right) + F_1 \left(\frac{162.22}{180.25} \right) = P \left(\frac{162.22}{207.30} \right) \frac{\text{kg FeCl}_3}{\text{kg tot}}$$

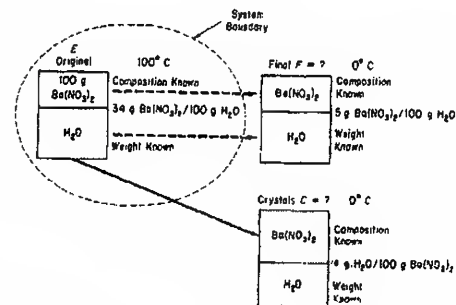
$$\text{Total: } 1000 + F_2 = P$$

$$\begin{array}{l} \text{soln} \\ F_2 = 1555.7 \text{ kg} \\ P = 2555.7 \text{ kg} \end{array}$$

Step 10: Check: $F_2 + F_1 = 1554.5 + 1000 = 2554.5$ ok

Solutions Chapter 8

8.18 Steps 2, 3, 4:



The process can be viewed as an unsteady process without reaction, or as a flow process.

Step 5: Take as a basis 100 g of $\text{Ba}(\text{NO}_3)_2$.

Step 4:

The maximum solubility of $\text{Ba}(\text{NO}_3)_2$ in H_2O at 100°C is a saturated solution, 34 g/100 g of H_2O . Thus the amount of water required at 100°C is

$$\frac{100 \text{ g H}_2\text{O}}{34 \text{ g Ba}(\text{NO}_3)_2} \left| \frac{100 \text{ g Ba}(\text{NO}_3)_2}{1} \right. = 294.1 \text{ g H}_2\text{O}$$

If the 100°C solution is cooled to 0°C , the $\text{Ba}(\text{NO}_3)_2$ solution will still be saturated so that the composition of the final solution is

$$\text{Ba}(\text{NO}_3)_2: \frac{\text{mass fr.}}{100 + 5} = 0.0476$$

(continued)

Solutions Chapter 8

$$\text{H}_2\text{O}: \frac{100}{100+5} = 0.9524$$

The composition of the crystals is

$$\text{Ba}(\text{NO}_3)_2: \frac{100}{100+4} = 0.9615$$

$$\text{H}_2\text{O}: \frac{4}{100+4} = 0.0385$$

The composition of the original solution is

		mass fr.
BaNO ₃	100g	0.254
H ₂ O	294.1g	0.746

Steps 6 and 7:

We have two unknowns, F and C , and can make two independent mass balances so that the problem has a unique solution.

Steps 8 and 9:

Balance	Final solution	Initial solution	Transport through boundary (out)
Ba(NO ₃) ₂ :	F(0.0476)	- 100	= -C(0.9615)
H ₂ O:	F(0.9524)	- 294.1	= -C(0.0385)
Total:	F	- (100 + 294.1)	= -C

Solve the Ba(NO₃)₂ and total balance to get

$$F = 305.2 \text{ g} \quad C = 88.89 \text{ g}$$

Step 10: Check using the water balance

$$305.2(0.9524) - 294.1 \stackrel{?}{=} -88.89(0.0385)$$

Solutions Chapter 8

$$-3.42 = -3.42$$

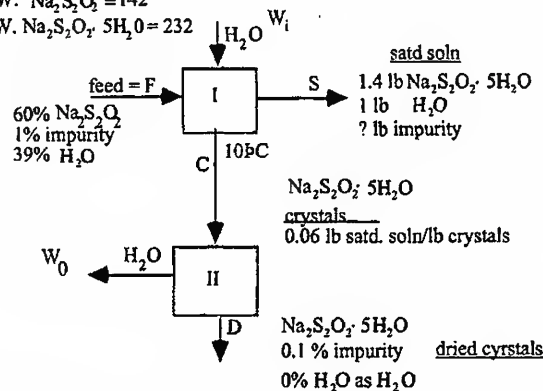
The Ba(NO₃)₂ that precipitates out on a dry basis is

$$\frac{88.89 \text{ g C}}{1 \text{ g C}} \left| \frac{0.9615 \text{ g Ba(NO}_3)_2}{1 \text{ g C}} \right| = \boxed{85.5 \text{ g Ba(NO}_3)_2}$$

8.19

M.W. Na₂S₂O₅ = 142

M.W. Na₂S₂O₅ · 5H₂O = 232



Process II Compositions:

a) Stream D Basis: 1 lb mol Na₂S₂O₅ · 5 H₂O, impurity free

Comp.	lb mol	mol wt	lb	wt fr	
Na ₂ S ₂ O ₅	1	142	142	0.612	
H ₂ O	5	18	90	0.388	
Total	6		232	1.000	(continued)

Solutions Chapter 8

Basis: 100 lb D ($\text{Na}_2\text{S}_2\text{O}_5 \cdot 5 \text{H}_2\text{O} = 99.9 \text{ lb}$)

Comp.		lb
$\text{Na}_2\text{S}_2\text{O}_5$	$99(0.612)$	= 61.1
H_2O	$99(0.388)$	= 38.8
impurity		<u>0.1</u>
Total		100.0

Stream C Let $y = \text{lb impurity}/100 \text{ lb free water}$ in saturated solution

Basis: 100 lb dry crystals, impurity free

lb from dry + lb from adhering soln

Comp.	crystals	from calculation below	= Total
$\text{Na}_2\text{S}_2\text{O}_5$	61.2	$(6) \left(\frac{85.7}{240 + y} \right)$	$61.2 + 6 \left(\frac{85.7}{240 + y} \right)$
H_2O	38.8	$(6) \left(\frac{154.3}{240 + y} \right)$	$38.8 + \left(\frac{154.3}{240 + y} \right)$
impurity	----	$(6) \left(\frac{y}{240 + y} \right)$	$\left(\frac{y}{240 + y} \right)$
Totals	100.0	6	106

Stream S Basis: 100 lb free water in satd. soln., impurity free

Comp.	lb from salt	lb from free water	Total	wt. fr.	wt.fr.total
$\text{Na}_2\text{S}_2\text{O}_5$	$1.4(61.2) = 85.68$			85.7	$0.357 \frac{85.7}{(240 + y)}$
H_2O	$1.4(38.8) = 54.32$	100		154.3	$0.643 \frac{154.3}{(240 + y)}$
	<u>140.00</u>	<u>100</u>		<u>240.0</u>	<u>1.000</u>

Solutions Chapter 8

$$\text{impurity} = \frac{y'}{240 + y}$$

Total

Basis: 100 lb F

(Rather than use the impurity balance, use the total balance instead if you want)

Water in, W_i , comes from balances on Unit I.

$$\text{Total: } 100 + W_i = S + C$$

$$\left. \begin{aligned} \text{Na}_2\text{S}_2\text{O}_5 \quad 60 &= \left(\frac{85.7}{240 + y} \right) S + \frac{61.2 + 6 \left(\frac{85.7}{240 + y} \right) C}{106} \\ \text{H}_2\text{O} \quad 39 + W_i &= \left(\frac{154.3}{240 + y} \right) S + \frac{38.8 + 6 \left(\frac{154.3}{240 + y} \right) C}{106} \end{aligned} \right\} \begin{array}{l} \text{Unknowns: } W_i, S, C, y \\ \text{Total: 4} \end{array}$$

Balances on Unit II needed as well because 4 unknowns exist.

$$\text{Total: } C = W_o + D$$

$$\left. \begin{aligned} \text{Na}_2\text{S}_2\text{O}_5 \quad \frac{61.2 + 6 \left(\frac{85.7}{240 + y} \right) C}{106} &= 0.611 D \\ \text{H}_2\text{O} \quad \frac{38.8 + 6 \left(\frac{154.3}{240 + y} \right) C}{106} &= W_o + 0.388 D \end{aligned} \right\} \begin{array}{l} \text{Unknowns: } W_o, D \\ \text{Total: 2} \end{array}$$

6 equations and 6 unknowns

Note that the complex term involving y can be eliminated to solve for D , W_o , W_i , and S , i.e., in (continued)

Solutions Chapter 8

effect making total $\text{Na}_2\text{S}_2\text{O}_5$ and H_2O balances overall the process.

The solution is (a) $W_1 = 23.34 \text{ lb}$ (b) 66.5%

8.20 Basis: 100 lb pulp as received

Comp	lb = %
H_2O	22
Pulp	78
Total	100

Freight cost = $\frac{\$1.00}{100 \text{ lb}} \left| \frac{2000 \text{ lb}}{1 \text{ ton}} \right| = \$20.00/\text{ton}$

Total 100

Assume air dried pulp means the 12% moisture pulp.

Allowed water = $\frac{78 \text{ lb pulp}}{88 \text{ lb pulp}} \left| \frac{12 \text{ lb } \text{H}_2\text{O}}{88 \text{ lb pulp}} \right| = 10.65 \text{ lb } \text{H}_2\text{O}$

Pulp on contract basis = $78 + 10.65 = 88.65 \text{ lb}$

Basis: 1 ton pulp as received

Cost = $\frac{88.65 \text{ lb } 12\% \text{ pulp rec'd}}{100 \text{ lb shipped}} \left| \frac{1 \text{ ton shipped}}{1 \text{ ton}} \right| \frac{\$60.00}{1 \text{ ton}} = \$53.19/\text{ton}$

8.21 You pay for soap plus transportation.

Basis: 100 kg soap with 30% water

Convert soap in wet soap to soap in dry soap. Data:

(continued)

Solutions Chapter 8

W (wet soap)	D (dry soap)
H_2O 30 kg	5%
soap 70 kg	95%
100 kg	100

Soap balance: $0.70W = 0.95D$ or $0.70(100) = 0.95D$

$D = 73.68 \text{ kg}$ of which 70 kg is soap

Cost of W at your site (containing 70 kg soap): $100 \left(\$0.30 + \frac{\$6.05}{100} \right) = \$36.05$

Cost of D at your site (containing 70 kg soap): $73.68 \left(\frac{x\$}{\text{kg}} + \frac{\$6.05}{100} \right) = \$36.05$

$x = \$0.43/\text{kg}$

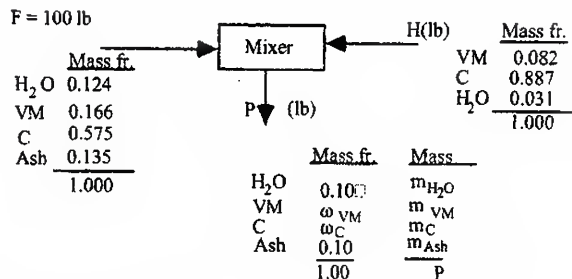
8.22

The problem here is to decide on the balances to make. Not all will be indept balances.

Steps 1, 2, 3, and 4:

(continued)

Solutions Chapter 8



Step 5: Basis: $F = 100 \text{ lb}$

Step 6: Unknowns: $m_{\text{H}_2\text{O}}, m_{\text{VM}}, m_{\text{C}}, m_{\text{Ash}}, P, H$ (6)

Step 7: Balances: $\text{H}_2\text{O}, \text{VM}, \text{C}, \text{Ash}, \Sigma m_i = P, m_{\text{H}_2\text{O}}/P = 0.10$
 $m_{\text{Ash}}/P = 0.10$: (7), and presumably 6 are independent

Steps 8 and 9:

	In	=	Out
$\text{H}_2\text{O} (\text{lb})$:	$100 (0.124) + H (0.082)$	=	$m_{\text{H}_2\text{O}}$
VM (lb)	$100 (0.166) + H (0.082)$	=	m_{VM}
C (lb)	$100 (0.575) + H (0.887)$	=	m_{C}
Ash (lb)	$100 (0.135) + H (0)$	=	m_{Ash}
Total	$100 + H$	=	P

Solution:

$$m_{\text{Ash}} = 13.5 \text{ lb} \quad m_{\text{H}_2\text{O}} = 13.5$$

(continued)

Solutions Chapter 8

Not all of the equations have to be written down as above. Note that ash is a tie element to P, so that the ash balance gives

$$100(0.135) + H(0) = P(0.10) \quad P = 135 \text{ lb} \quad \text{and } m_{\text{Ash}} = 13.5 \text{ lb}$$

From a total balance

$$H + 100 = P \quad \boxed{H = 35 \text{ lb}}$$

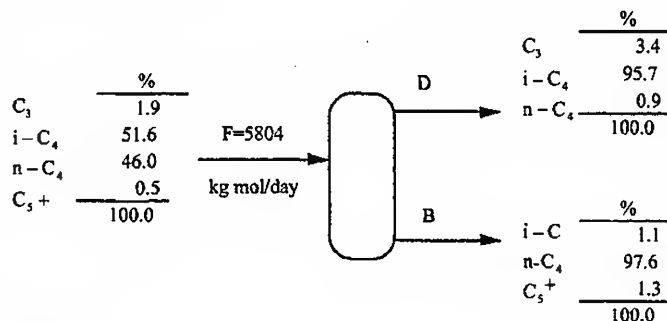
Step 10: Check via H_2O balance

$$\left. \begin{array}{l} 12.4 + 35(0.031) = 13.5 \\ 13.49 = 13.5 \end{array} \right\} \text{ok}$$

Solutions Chapter 8

8.23 Step 5: Basis: 1 day

Steps 2, 3, and 4:



Steps 6 and 7:

There are two unknowns, and we have 4 independent equations, but the precision of measurement is not the same in each equation, hence different results are obtained depending on the equations used. Choose the most accurate to use.

	In		Out
C ₃	(0.019)(5804) = 110	=	0.034D
i-C ₄	2992	=	0.057D + 0.011B
n-C ₄	2667	=	0.009D + 0.976B
C ₅ ⁺	37	=	0.013B
Total:	5804	=	D + B

Steps 8 and 9:

Solutions Chapter 8

Use total + i-C₄ balances:

$$2992 = 0.975(5804 - B) + 0.011B$$

kg mol/day

$$B = 2563$$

$$D = 3240$$

Use total + n-C₄ balances:

$$2667 = 0.009(5804 - B) + 0.976B$$

$$B = 2704$$

$$D = 3100$$

The other two balances give

C₃ as a tie component:

$$\frac{5804 \text{ kg mol F}}{1 \text{ day}} \left| \frac{0.019 \text{ kg mol C}_3}{1.00 \text{ kg mol F}} \right| \frac{1 \text{ kg mol D}}{0.034 \text{ kg mol C}_3} = 3243 \frac{\text{kg mol D}}{\text{day}}$$

C₅⁺ as a tie element:

$$\frac{5804 \text{ kg mol F}}{1 \text{ day}} \left| \frac{0.006 \text{ kg mol C}_5^+}{1.00 \text{ kg mol F}} \right| \frac{1 \text{ kg mol B}}{0.013 \text{ kg mol C}_5^+} \approx 2679 \text{ kg mol B / day}$$

8.24

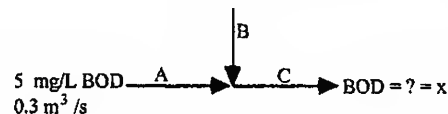
Steps 1, 2, 3, and 4:

Assume the other components have the same density as water in all flows.

a.

$$3.785 \times 10^6 \text{ L/day}$$

$$150 \text{ mg/L BOD}$$



Step 5: Basis: 1 day

(continued)

Solutions Chapter 8

$$A = \frac{0.3 \text{ m}^3}{\text{s}} \left| \frac{3600 \text{ s}}{\text{hr}} \right| \left| \frac{24 \text{ hr}}{\text{day}} \right| \left| \frac{1000 \text{ L}}{\text{m}^3} \right| = 2.592 \times 10^7 \text{ L / day}$$

Steps 6 and 7:

Unknowns: C, x

Balances: H₂O, BOD

Steps 8 and 9:

Total mass balance A + B = C

$$\frac{1 \text{ day}}{\text{day}} \left| \frac{A \text{ L}}{\text{day}} \right| \left| \frac{1 \text{ kg}}{\text{L}} \right| + \frac{1 \text{ day}}{\text{day}} \left| \frac{B \text{ L}}{\text{day}} \right| \left| \frac{1 \text{ kg B}}{\text{L}} \right| = \frac{1 \text{ day}}{\text{day}} \left| \frac{C \text{ L}}{\text{day}} \right| \left| \frac{1 \text{ kg C}}{\text{L}} \right|$$

BOD mass balance

$$\frac{1 \text{ day}}{\text{day}} \left| \frac{A \text{ L}}{\text{day}} \right| \left| \frac{5 \times 10^{-3} \text{ g BOD}}{\text{L}} \right| + \frac{1 \text{ day}}{\text{day}} \left| \frac{B \text{ L}}{\text{day}} \right| \left| \frac{150 \times 10^{-3} \text{ g BOD}}{\text{day}} \right| = \frac{1 \text{ day}}{\text{day}} \left| \frac{C \text{ L}}{\text{day}} \right| \left| \frac{x \text{ g BOD}}{\text{L}} \right|$$

$$2.592 \times 10^7 \text{ kg} + 3.785 \times 10^6 \text{ kg} = C = 2.9705 \times 10^7 \text{ kg}$$

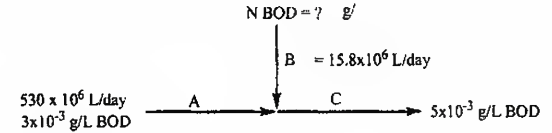
$$5 \times 10^{-3} A + 150 \times 10^{-3} B = xC$$

$$x = \frac{5 \times 10^{-3} A + 150 \times 10^{-3} B}{C}$$

$$= \frac{5 \times 10^{-3} (2.592 \times 10^7) + 150 \times 10^{-3} (3.785 \times 10^6)}{2.9705 \times 10^7} = \boxed{23.475 \times 10^{-3} \text{ g / L}}$$

Solutions Chapter 8

b.



Total mass balance A + B = C

$$\frac{1 \text{ day}}{\text{day}} \left| \frac{A \text{ L}}{\text{day}} \right| \left| \frac{1 \text{ kg}}{\text{L}} \right| + \frac{1 \text{ day}}{\text{day}} \left| \frac{B \text{ L}}{\text{day}} \right| \left| \frac{1 \text{ kg}}{\text{L}} \right| = \frac{1 \text{ day}}{\text{day}} \left| \frac{C \text{ L}}{\text{day}} \right| \left| \frac{1 \text{ kg}}{\text{L}} \right|$$

$$530 \times 10^6 \text{ kg} + 15.8 \times 10^6 \text{ kg} = C = 5.458 \times 10^8 \text{ kg}$$

BOD mass Balance

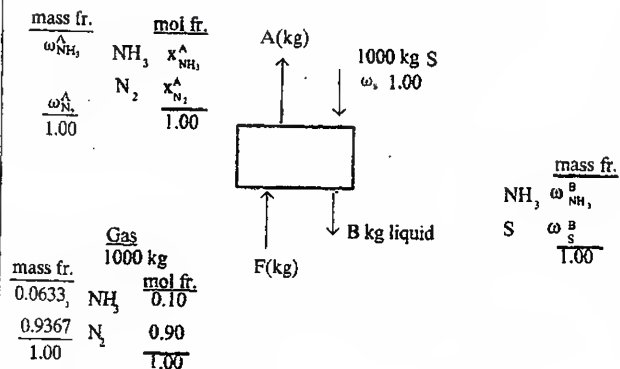
$$\frac{1 \text{ day}}{\text{day}} \left| \frac{A \text{ L}}{\text{day}} \right| \left| \frac{3 \times 10^{-3} \text{ g BOD}}{\text{L}} \right| + \frac{1 \text{ day}}{\text{day}} \left| \frac{B \text{ L}}{\text{day}} \right| \left| \frac{N \times 10^{-3} \text{ g}}{\text{L}} \right| = \frac{1 \text{ day}}{\text{day}} \left| \frac{C \text{ L}}{\text{day}} \right| \left| \frac{5 \times 10^{-3} \text{ g}}{\text{L}} \right|$$

$$3 \times 10^{-3} A + N \times 10^{-3} B = 5 \times 10^{-3} C$$

$$N = \frac{5 \times 10^{-3} C - 3 \times 10^{-3} A}{B}$$

$$= \frac{(5 \times 10^{-3})(5.458 \times 10^8) - (3 \times 10^{-3})(5.30 \times 10^8)}{1.58 \times 10^7} = \boxed{72.1 \times 10^{-3} \text{ g / L}} \text{ ok}$$

Solutions Chapter 8



Step 5: Basis 1.0 hr

Step 6: The unknowns are A, B, $\omega_{\text{NH}_3}^A$, $\omega_{\text{N}_2}^A$, $\omega_{\text{NH}_3}^B$, ω_{S}^B , a total of 6.

Steps 7 and 8: Three compound balances can be made, N_2 , NH_3 , and S. One relation is given:

$$\omega_{\text{NH}_3}^A = 2\omega_{\text{NH}_3}^B$$

Two summations exist: $\sum \omega_i^A = 1$ and $\sum \omega_i^B = 1$

hence, we have an adequate number of balances (unless some are not independent) to solve the problem.

Step 4: (revisited) Material balance equations in grams

Total: $F + S = A + B$
 $1000 + 1000 = A + B$

Solutions Chapter 8

$$\text{NH}_3: 1000(0.0633) + 0 = A\omega_{\text{NH}_3}^A + B\omega_{\text{NH}_3}^B = 1$$

$$\text{N}_2: 1000(0.9367) + 0 = A\omega_{\text{N}_2}^A + 0$$

$$\text{S: } 0 + 1000 = 0 + B\omega_{\text{S}}^B$$

Constraints

$$\omega_{\text{NH}_3}^A + \omega_{\text{N}_2}^A = 1$$

$$\omega_{\text{NH}_3}^B + \omega_{\text{S}}^B = 1$$

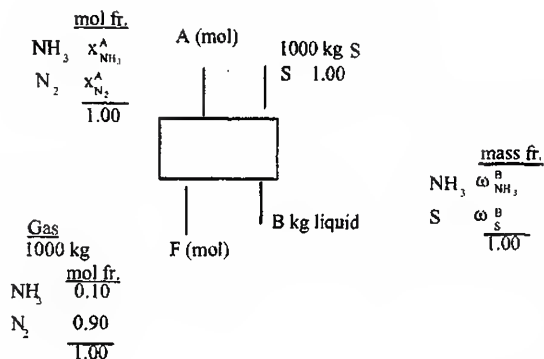
$$\omega_{\text{NH}_3}^A = 2\omega_{\text{NH}_3}^B$$

Solve in Polymath

Note: the equations can be converted to linear equations by letting $m_{\text{NH}_3}^A = \omega_{\text{NH}_3}^A A$, $m_{\text{N}_2}^A = \omega_{\text{N}_2}^A A$, etc.

The set can be solved in Polymath or reduced to a quadratic equation in $m_{\text{NH}_3}^B$ or $m_{\text{NH}_3}^A$.

Solutions Chapter 8



Step 5: Basis 1.0 hr

Step 6: The unknowns are A, B, $x_{NH_3}^A$, $x_{N_2}^A$, $\omega_{NH_3}^B$, ω_S^B , a total of 6.

Steps 7 and 8: Three compound balances can be made, N_2 , NH_3 , and S. One relation is given:

$$\omega_{NH_3}^A = 2\omega_{NH_3}^B$$

Two summations exist: $\sum x_i^A = 1$ and $\sum \omega_i^B = 1$

hence, we have an adequate number of balances (unless some are not independent) to solve the problem.

Step 4: (revisited) Find the moles of F by getting the average molecular weight of F.

Basis: 1 g mol F

Solutions Chapter 8

	mole fr	MW	mass (g)
NH_3	0.10	17.03	1.703
N_2	0.90	28.0	25.200
	1.00		26.903

$$\frac{1000 \text{ kg F}}{26.903 \text{ kg F}} \times \frac{1 \text{ kg mol F}}{26.903 \text{ kg F}} = 37.171 \text{ kg mol}$$

Steps 7 and 8: (repeated) The balances are

	In	Out
NH_3 (kg mol):	$0.10 (37.171) + 0 (1000) MW_S = \frac{\omega_{NH_3}^B (B)}{17.03} + x_{NH_3}^A (A)$	
N_2 (kg mol):	$0.90 (37.171) + 0 (1000) MW_S = 0 (B) + x_{N_2}^A (A)$	
S (kg):	$0 (1000) + 1000 = \omega_S^B (B) S + 0 (A) MW_A$	
	$x_{NH_3}^A + x_{N_2}^A = 1.00$	$\omega_{NH_3}^B + \omega_S^B = 1.00$
		$\omega_{NH_3}^A = 2\omega_{NH_3}^B$

N_2 and S are tie components. Let $x_{NH_3}^A A = n_{NH_3}^A$, let $x_{N_2}^A A = n_{N_2}^A$, and $\omega_{NH_3}^B B = m_{NH_3}^B$, etc. Then $n_{NH_3}^A + n_{N_2}^A = A$, and $m_{NH_3}^B + m_S^B = B$

Step 9: A total balance of 1000 + 1000 in kg, but not if in moles, can be used in lieu of one of the above balances. They give

(continued)

Solutions Chapter 8

The results are: $m_1^B = 1000 \text{ kg}$

$$n_{N_2}^A = 0.90(37.171) = 33.45 \text{ kg mol}$$

$$\omega_{HNH_3}^B = 0.0212 \quad A = 978 \text{ g}$$

$$\omega_S^B = 0.979 \quad B = 1021.7 \text{ g}$$

$$\omega_{HNH_3}^B = 0.0425 \quad x_{NH_3}^A = 0.0681$$

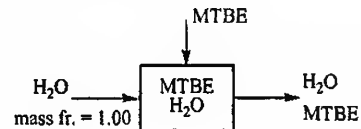
$$\omega_{N_2}^A = 0.958 \quad x_{N_2}^B = 0.932$$

Solutions Chapter 8

8.27

Basis: 12 hours

The process is illustrated in the figure



The MTBE entering the pond in 12 hours is

$$\frac{25 \text{ boats}}{1 \text{ boat}} \left| \frac{0.5 \text{ L gasoline}}{1 \text{ L}} \right| \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right| \left| \frac{0.72 \text{ g}}{1 \text{ cm}^3} \right| \left| \frac{0.10 \text{ g MTBE}}{1 \text{ g gasoline}} \right| = 900 \text{ g MTBE}$$

The pond holds (ignoring the MTBE in the pond which is negligible)

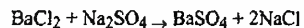
$$\frac{3000 \text{ m}}{1} \left| \frac{1,000 \text{ m}}{1} \right| \left| \frac{3 \text{ m}}{1} \right| \left| \frac{1000 \text{ kg H}_2\text{O}}{1 \text{ m}^3 \text{ H}_2\text{O}} \right| = 9 \times 10^9 \text{ kg H}_2\text{O}$$

The increase in the concentration of MTBE is

$$\frac{900 \text{ g MTBE}}{9 \times 10^9 \text{ kg H}_2\text{O}} \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| = \boxed{1 \times 10^{-10} \text{ g MTBE/g H}_2\text{O}}$$

Solutions Chapter 9

9.1



Mol. wt.: 208.3 142.05 233.4 58.45

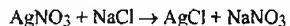
a. Basis: 5.0 g Na_2SO_4

$$\text{Example: } \frac{5 \text{ g Na}_2\text{SO}_4}{142.05 \text{ g Na}_2\text{SO}_4} \times \frac{1 \text{ g mol Na}_2\text{SO}_4}{1 \text{ g mol Na}_2\text{SO}_4} \times \frac{1 \text{ g mol BaCl}_2}{1 \text{ g mol BaCl}_2} \times \frac{208.3 \text{ g BaCl}_2}{1 \text{ g mol BaCl}_2} =$$

7.33 g BaCl_2

Problem	Basis	Answer
b.	5 g BaSO_4	4.47 g BaCl_2
c.	5 g NaCl	8.91 g BaCl_2
d.	5 g BaCl_2	3.41 g Na_2SO_4
e.	5 g BaSO_4	3.04 g Na_2SO_4
f.	5 lb NaCl	6.08 lb Na_2SO_4
g.	5 lb BaCl_2	5.59 lb BaSO_4
h.	5 lb Na_2SO_4	8.21 lb BaSO_4
i.	5 lb NaCl	9.98 lb BaSO_4

9.2



Mol. wt.: 169.89 58.45 143.3 85.01

a. Basis: 5.0 g NaCl

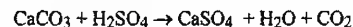
$$\text{Example: } \frac{5.0 \text{ g NaCl}}{58.45 \text{ g NaCl}} \times \frac{1 \text{ g mol NaCl}}{1 \text{ g mol NaCl}} \times \frac{1 \text{ g mol AgNO}_3}{1 \text{ g mol NaCl}} \times \frac{169.89 \text{ g AgNO}_3}{1 \text{ g mol AgNO}_3} =$$

14.53 g AgNO_3

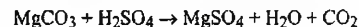
Solutions Chapter 9

Problem	Basis	Answer
b.	5 g AgCl	5.92 g AgNO_3
c.	5 g NaNO_3	10.00 g AgNO_3
d.	5 g AgNO_3	1.721 g NaCl
e.	5 g AgCl	2.04 g NaCl
f.	5 lb NaNO_3	3.44 lb NaCl
g.	5 lb AgNO_3	4.22 lb AgCl
h.	5 lb NaCl	12.27 lb AgCl
i.	5 lb AgNO_3	4.22 lb AgCl

9.3 Basis: 1 ton dolomite



Assume complete reactions



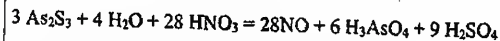
Comp.	%	lb	mol.wt.	lb mol that react
CaCO_3	68	1360	100.0	13.60
MgCO_3	30	600	84.3	7.13
SiO_2	2	40	60.0	
Total	100	2000		20.73

$$\text{a. } \frac{20.73 \text{ lb mol react}}{\text{ton dolomite}} \times \frac{1 \text{ mol CO}_2 \text{ produced}}{1 \text{ mol react}} \times \frac{44 \text{ lb}}{1 \text{ lb mol CO}_2} = 912 \text{ lb CO}_2$$

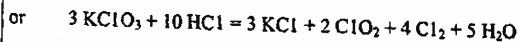
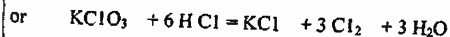
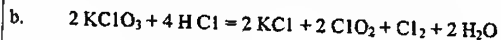
$$\text{b. } \frac{20.73 \text{ lb mol react}}{\text{ton dolomite}} \times \frac{1 \text{ mol H}_2\text{SO}_4 \text{ reqd}}{1 \text{ mol react}} \times \frac{98 \text{ lb H}_2\text{SO}_4}{1 \text{ mole H}_2\text{SO}_4} \times \frac{100 \text{ lb acid}}{94 \text{ lb H}_2\text{SO}_4} = 2160 \text{ lb acid}$$

9.4

a. The balanced equation is:



and the reaction is unique within relative proportions.



We classify these reactions as non-unique since they are not simply proportional equations, but are linearly independent, and infinitely many equations can be obtained by linear combination.

9.5 Basis: Data given in problem statement

$$\frac{55.847 \text{ g Fe}}{1} \left| \frac{1 \text{ gmol Fe}}{55.847 \text{ g Fe}} \right| \left| \frac{1 \text{ gmol } \text{X}_2\text{O}_3}{2 \text{ gmol Fe}} \right| \left| \frac{2 \text{ gmol X}}{1 \text{ gmol } \text{X}_2\text{O}_3} \right| = 1 \text{ gmol X}$$

$$\frac{55.847 \text{ g Fe}}{1} \left| \frac{1 \text{ gmol Fe}}{55.847 \text{ g Fe}} \right| \left| \frac{1 \text{ gmol } \text{X}_2\text{O}_3}{2 \text{ gmol Fe}} \right| \left| \frac{3 \text{ gmol O}}{1 \text{ gmol } \text{X}_2\text{O}_3} \right| \left| \frac{16 \text{ g O}}{1 \text{ gmol O}} \right| = 24.0 \text{ g O}$$

$$50.982 \text{ g } \text{X}_2\text{O}_3 - 24.0 \text{ g O} = 26.982 \text{ g X}$$

$$\frac{26.982 \text{ g X}}{1 \text{ gmol X}} = 26.982 \frac{\text{g}}{\text{gmol}} \text{ hence X = Al}$$

9.6 Basis: Data given in problem statement

$$\frac{1.603 \text{ g CO}_2}{1} \left| \frac{1 \text{ gmol CO}_2}{44.01 \text{ g CO}_2} \right| \left| \frac{1 \text{ gmol C}}{1 \text{ gmol CO}_2} \right| \left| \frac{12.00 \text{ g C}}{1 \text{ gmol C}} \right| = 0.437 \text{ g C}$$

$$\frac{0.2810 \text{ g H}_2\text{O}}{1} \left| \frac{1 \text{ gmol H}_2\text{O}}{18.02 \text{ g H}_2\text{O}} \right| \left| \frac{2 \text{ gmol H}}{1 \text{ gmol H}_2\text{O}} \right| \left| \frac{1.008 \text{ g H}}{1 \text{ gmol H}} \right| = 0.03144 \text{ g H}$$

$$0.6349 \text{ g C}_x\text{H}_y\text{O}_z - 0.437 \text{ g C} - 0.03144 \text{ g H} = 0.1661 \text{ g O}$$

Based on O:

$$\frac{0.1661 \text{ g O}}{1} \left| \frac{1 \text{ gmol O}}{16.00 \text{ g O}} \right| = \frac{0.01038 \text{ gmol O}}{0.01038} = 1 \text{ gmol O}$$

$$\frac{0.437 \text{ g C}}{1} \left| \frac{1 \text{ gmol C}}{12.00 \text{ g C}} \right| = \frac{0.03642 \text{ gmol C}}{0.01038} = 3.5 \text{ gmol C}$$

$$\frac{0.03144 \text{ g H}}{1} \left| \frac{1 \text{ gmol H}}{1.008 \text{ g H}} \right| = \frac{0.03119 \text{ gmol H}}{0.01038} = 3 \text{ gmol H}$$

The formula in integers is



Solutions Chapter 9

9.7 Basis: Data given in the problem

Mass of hydrate	10.407 g
Mass of dry sample	-9.520 g
Mass of water	0.887 g

$$\frac{9.520 \text{ g BaI}_2}{391 \text{ g BaI}_2} \left| \frac{1 \text{ g mol BaI}_2}{1 \text{ g BaI}_2} \right| = 0.0243 \text{ g mol BaI}_2$$

$$\frac{0.887 \text{ g H}_2\text{O}}{18.02 \text{ g H}_2\text{O}} \left| \frac{1 \text{ g mol H}_2\text{O}}{1 \text{ g H}_2\text{O}} \right| = 0.0493 \text{ g mol H}_2\text{O}$$

$$\frac{0.0243}{0.0493} = 0.49, \text{ or } 2 \text{ H}_2\text{O for } 1 \text{ BaI}_2. \text{ Thus the hydrate is } \text{BaI}_2 \cdot 2\text{H}_2\text{O}.$$

9.8 Basis: 2 g mol

$$\begin{aligned} \text{C: } 6 \times 12 &= 72 & \text{H: } 8 \times 1 &= 8 & \text{O: } 6 \times 16 &= 96 \\ \text{mol. wt.} &= 72 + 8 + 96 = 176 \end{aligned}$$

$$\frac{2 \text{ g mol}}{1 \text{ g mol}} \left| \frac{176 \text{ g}}{176 \text{ g}} \right| \left| \frac{1 \text{ lb}}{454 \text{ g}} \right| = 0.775 \text{ lb}$$

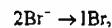
Solutions Chapter 9

9.9 Basis: 2000 tons 93.2% H₂SO₄ (1 day)

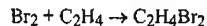
$$\text{a. } \frac{2000 \text{ tons soln}}{1 \text{ ton soln}} \left| \frac{0.932 \text{ ton H}_2\text{SO}_4}{1 \text{ ton soln}} \right| \left| \frac{1 \text{ ton mole H}_2\text{SO}_4}{98 \text{ ton H}_2\text{SO}_4} \right| \left| \frac{1 \text{ mol S}}{1 \text{ mol H}_2\text{SO}_4} \right| \left| \frac{32 \text{ ton S}}{1 \text{ ton mol S}} \right| = 609 \text{ ton S}$$

$$\text{b. } \frac{609 \text{ ton S}}{32 \text{ ton S}} \left| \frac{1 \text{ ton mol S}}{1 \text{ mol S}} \right| \left| \frac{1.5 \text{ mol O}_2}{1 \text{ mol S}} \right| \left| \frac{32 \text{ ton O}_2}{1 \text{ ton mol O}_2} \right| = 913.5 \text{ ton O}_2$$

$$\text{c. } \frac{609 \text{ ton S}}{32 \text{ ton S}} \left| \frac{1 \text{ ton mole S}}{1 \text{ mol S}} \right| \left| \frac{1 \text{ mole H}_2\text{O}}{1 \text{ mol S}} \right| \left| \frac{18 \text{ ton H}_2\text{O}}{1 \text{ ton mol H}_2\text{O}} \right| = 342.6 \text{ ton H}_2\text{O}$$

9.10 Basis: 1 lb Br₂

$$\text{MW: } \quad 70.9 \quad 159.8$$



$$\text{MW: } \quad 28 \quad 187.9$$

$$\text{a. } \frac{0.27 \text{ lb acid}}{2000 \text{ lb seawater}} \left| \frac{1 \times 10^6 \text{ lb seawater}}{65 \text{ lb Br}_2} \right| = 2.08 \text{ lb } 98\% \text{ H}_2\text{SO}_4 / \text{lb Br}_2$$

$$\text{b. } \frac{1 \text{ lb Br}_2}{159.9 \text{ lb Br}_2} \left| \frac{\text{mole Br}_2}{1 \text{ mole Br}_2} \right| \left| \frac{1 \text{ mole Cl}_2}{1 \text{ mole Br}_2} \right| \left| \frac{70.9 \text{ lb Cl}_2}{1 \text{ mole Cl}_2} \right| = 0.445 \text{ lb Cl}_2$$

$$\text{c. } \frac{1 \text{ lb Br}_2}{65 \text{ lb Br}_2} \left| \frac{1 \times 10^6 \text{ lb sea water}}{1 \text{ lb Br}_2} \right| = 15,400 \text{ lb seawater}$$

$$\text{d. } \frac{1 \text{ lb Br}_2}{159.9 \text{ lb Br}_2} \left| \frac{\text{mole Br}_2}{1 \text{ mole Br}_2} \right| \left| \frac{1 \text{ mole C}_2\text{H}_4\text{Br}_2}{1 \text{ mole Br}_2} \right| \left| \frac{187.9 \text{ lb C}_2\text{H}_4\text{Br}_2}{1 \text{ mole C}_2\text{H}_4\text{Br}_2} \right| = 1.176 \text{ lb C}_2\text{H}_4\text{Br}_2$$

Solutions Chapter 9

9.11

a)	<u>LHS</u>	<u>RHS</u>
C	4	4
H	10	10
Zn	1	1
O	14	14

Yes, the equation is balanced.

b) Basis: 1.5 kg ZnO

$$\frac{1.5 \text{ kg ZnO}}{1.0 \text{ kg ZnO}} \left| \frac{1000 \text{ g ZnO}}{81.40 \text{ g ZnO}} \right| \frac{1 \text{ gmol ZnO}}{1 \text{ gmol ZnO}} \left| \frac{1 \text{ gmol DEZ}}{1 \text{ gmol ZnO}} \right| \frac{123.4 \text{ gDEZ}}{1 \text{ gmol DEZ}}$$

$$\times \frac{1.0 \text{ kg DEZ}}{1000 \text{ g DEZ}} = \boxed{2.27 \text{ kg DEZ}}$$

$$\text{c) } \frac{20 \text{ cm}^3 \text{ H}_2\text{O}}{1 \text{ cm}^3 \text{ H}_2\text{O}} \left| \frac{1.0 \text{ g H}_2\text{O}}{18.0 \text{ g H}_2\text{O}} \right| \frac{1.0 \text{ gmol H}_2\text{O}}{5 \text{ gmol H}_2\text{O}} \left| \frac{1 \text{ gmol DEZ}}{1 \text{ gmol H}_2\text{O}} \right| \frac{123.4 \text{ g DEZ}}{1 \text{ gmol DEZ}}$$

$$= \boxed{27.4 \text{ g DEZ}}$$

Solutions Chapter 9

9.12

$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	$\frac{\text{MW}}{277.9}$	$\text{FeSO}_4 \cdot \text{H}_2\text{O}$	$\frac{\text{MW}}{169.9}$
$\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$	223.9	FeSO_4	151.9

It is best to evaluate the three types of ferrous sulfate in terms of the cost/ton of FeSO_4

Basis: 475 ton material

a. $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$:

$$\frac{\$83,766.25}{475 \text{ ton FeSO}_4 \cdot 7\text{H}_2\text{O}} = \$176.35/\text{ton FeSO}_4 \cdot 7\text{H}_2\text{O} \text{ which is equivalent to}$$

$$\frac{\$176.35}{1 \text{ ton FeSO}_4 \cdot 7\text{H}_2\text{O}} \left| \frac{277.9 \text{ ton FeSO}_4 \cdot 7\text{H}_2\text{O}}{1 \text{ ton mol FeSO}_4 \cdot 7\text{H}_2\text{O}} \right| \frac{1 \text{ ton mol FeSO}_4 \cdot 7\text{H}_2\text{O}}{1 \text{ ton mol FeSO}_4}$$

$$\frac{1 \text{ ton mol FeSO}_4}{151.9 \text{ ton FeSO}_4} = \$323/\text{ton FeSO}_4$$

b. $\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$:

$$\frac{\$323}{\text{ton FeSO}_4} \left| \frac{151.9 \text{ ton FeSO}_4}{1 \text{ ton mol FeSO}_4} \right| \frac{1 \text{ ton mol FeSO}_4}{1 \text{ ton mol FeSO}_4 \cdot 4\text{H}_2\text{O}} \left| \frac{1 \text{ ton mol FeSO}_4 \cdot 4\text{H}_2\text{O}}{223.9 \text{ ton FeSO}_4 \cdot 4\text{H}_2\text{O}} \right|$$

$$= \boxed{\$219/\text{ton FeSO}_4 \cdot 4\text{H}_2\text{O}}$$

c. $\text{FeSO}_4 \cdot \text{H}_2\text{O}$:

$$\frac{\$323}{\text{ton FeSO}_4} \left| \frac{151.9 \text{ ton FeSO}_4}{1 \text{ ton mol FeSO}_4} \right| \frac{1 \text{ ton mol FeSO}_4}{1 \text{ ton mol FeSO}_4 \cdot \text{H}_2\text{O}} \left| \frac{1 \text{ ton mol FeSO}_4 \cdot \text{H}_2\text{O}}{169.9 \text{ ton FeSO}_4 \cdot \text{H}_2\text{O}} \right|$$

$$= \boxed{\$289/\text{ton FeSO}_4 \cdot \text{H}_2\text{O}}$$

Solutions Chapter 9

9.13 The reaction is $\text{C}_4\text{H}_{10} + 6\frac{1}{2}\text{O}_2 \rightarrow 4\text{CO}_2 + 5\text{H}_2\text{O}$

Basis: 1 mol C_4H_{10}

$$\text{Minimum O}_2 \cong (\text{LFL}) \left(\frac{\text{mol O}_2 \text{ for complete combustion}}{\text{mol C}_4\text{H}_{10}} \right)$$

$$\cong (1.9\%) (6.5/1) = \boxed{12.4\%}$$

9.14 Basis: 1 L solution = 1000 g H_2O

$$\frac{50 \text{ g H}_2\text{S}}{10^6 \text{ g soln}} \left| \frac{1 \text{ g mol H}_2\text{S}}{34 \text{ g H}_2\text{S}} \right| \left| \frac{1 \text{ g mol HOCl}}{1 \text{ g mol H}_2\text{S}} \right| \left| \frac{52.45 \text{ g HOCl}}{1 \text{ g mol HOCl}} \right| \left| \frac{100 \text{ g HOCl soln}}{5 \text{ g HOCl}} \right|$$

$$\frac{1000 \text{ g soln}}{1 \text{ L soln}} \left| \frac{2}{1} \right| = \boxed{3.08 \text{ g HOCl solution}}$$

You can use the density of H_2O for the density of the solution as the H_2S content has negligible effect on the density.

Solutions Chapter 9

9.15 $\text{Na}_2\text{CO}_3 + \text{Ca}(\text{OH})_2 \rightarrow 2\text{NaOH} + \text{CaCO}_3$

Basis: 1 ton of soda ash (Na_2CO_3)

$$\frac{1 \text{ ton Na}_2\text{CO}_3}{106 \text{ ton Na}_2\text{CO}_3} \left| \frac{1 \text{ ton mol Na}_2\text{CO}_3}{1 \text{ ton mol Na}_2\text{CO}_3} \right| \left| \frac{2 \text{ ton mol NaOH}}{1 \text{ ton mol Na}_2\text{CO}_3} \right| \left| \frac{40.0 \text{ ton NaOH}}{1 \text{ ton mol NaOH}} \right| =$$

0.755 ton NaOH

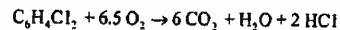
$$\frac{\$130}{1 \text{ ton Na}_2\text{CO}_3} \left| \frac{1 \text{ ton Na}_2\text{CO}_3}{0.755 \text{ NaOH}} \right| = \boxed{\$172 / \text{ton Na}_2\text{CO}_3}$$

The above result is for the case of free $\text{Ca}(\text{OH})_2$. Otherwise, the value must be reduced to compensate for the cost of the $\text{Ca}(\text{OH})_2$ -- which might come from the CaCO_3 produced, and possibly be cheaper than $\text{Ca}(\text{OH})_2$ purchased directly.

Solutions Chapter 9

9.16 Basis: 1 kg dichlorobenzene (DCB)

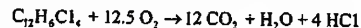
The balanced stoichiometric reaction for dichlorobenzene is shown below:



Therefore, for 1 kg of dichlorobenzene, the following moles of HCl are produced:

$$\frac{1 \text{ kg DCB}}{147 \text{ kg DCB}} \left| \frac{1 \text{ kg mol DCB}}{1 \text{ kg mol DCB}} \right| \frac{2 \text{ kg mol HCl}}{1 \text{ kg mol DCB}} = 0.0136 \text{ kg mol HCl}$$

The balanced stoichiometric reaction for tetrachlorobiphenyl is as shown below:



Therefore, for 1 lb of tetrachlorobiphenyl (TCB), the following moles of HCl are produced:

Basis: 1 kg TCB

$$\frac{1 \text{ kg TCB}}{290 \text{ kg TCB}} \left| \frac{1 \text{ kg mol TCB}}{1 \text{ kg mol TCB}} \right| \frac{4 \text{ kg mol HCl}}{1 \text{ kg mol TCB}} = 0.0138 \text{ kg mol HCl}$$

Thus, the amount of acid produced does not change significantly ($\approx 1.5\%$), and neither will the amount of base required for neutralization.

Solutions Chapter 9

9.17 Basis: 10 lb moles phosgene

For phosgene:

$$\xi = \frac{n_f - n_i}{1} = \frac{10 - 0}{1} = \boxed{10} \text{ reacting moles}$$

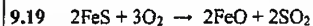
$$n_{\text{CO}_2} = n_{\text{CO}_2, f} - \nu_{\text{CO}_2} \xi = 7 - (-1)(10) = \boxed{17 \text{ lb mol}}$$

$$n_{\text{C}_2\text{H}_2} = n_{\text{C}_2\text{H}_2, f} - \nu_{\text{C}_2\text{H}_2} \xi = 3 - (-1)(10) = \boxed{13 \text{ lb mol}}$$

9.18 Basis: 135 mol CH₄

$$\xi = \frac{0 - 135}{-6} = \boxed{22.5 \text{ reacting mols}}$$

Solutions Chapter 9



MW 87.85 32 71.85 64

Basis: Use 100 g slag

Component	g = %	MW	g mol
FeO	80	71.85	1.113
Fes	20	87.85	0.228
	100		

For the FeO:

$$\xi = \frac{n_f - n_i}{\nu} = \frac{1.113 - 0}{2} = 0.557 \text{ reacting moles}$$

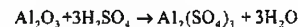
For the FeS:

$$\xi = \frac{n_f - n_i}{\nu} = \frac{0.228 - 0}{-2} = 0.557$$

$$n_{\text{initial FeS}} = 1.341 \text{ g mol}$$

Solutions Chapter 9

9.20 Basis: 1080 lb bauxite



$$\frac{1080 \text{ lb bauxite}}{100 \text{ lb bauxite}} \left| \frac{55.4 \text{ lb Al}_2\text{O}_3}{100 \text{ lb bauxite}} \right| \left| \frac{1 \text{ lb mol Al}_2\text{O}_3}{101.9 \text{ lb Al}_2\text{O}_3} \right| = 5.87 \text{ lb mol Al}_2\text{O}_3$$

$$\xi = \frac{0 - 5.87}{-1} = 5.87 \text{ reacting moles}$$

Basis: 2510 lb H₂SO₄ (77%)

$$\frac{2510 \text{ lb H}_2\text{SO}_4 (77\%)}{1 \text{ lb H}_2\text{SO}_4 (77\%)} \left| \frac{0.77 \text{ lb H}_2\text{SO}_4}{98.1 \text{ lb H}_2\text{SO}_4} \right| \left| \frac{1 \text{ lb mol H}_2\text{SO}_4}{98.1 \text{ lb H}_2\text{SO}_4} \right| = 19.70 \text{ lb mol H}_2\text{SO}_4$$

$$\xi = \frac{0 - 19.70}{-3} = 6.57 \text{ reacting moles}$$

(a) Al₂O₃ is the limiting reactant and H₂SO₄ is the excess reactant.

$$(b) \% \text{xs H}_2\text{SO}_4: \frac{(19.70)(1/3) - 5.87}{5.87} (100) = \frac{6.57 - 5.87}{5.87} (100) = 11.9\%$$

$$\text{or H}_2\text{SO}_4 (77\%) \text{ required: } \frac{(5.87)(3)(98.1)}{0.77} = 2244 \text{ lb}$$

$$\% \text{xs} = \frac{2510 - 2244}{2244} = 12\%$$

Basis: 2000 lb Al₂(SO₄)₃

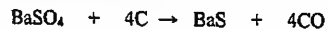
$$\frac{2000 \text{ lb Al}_2(\text{SO}_4)_3}{342.1 \text{ lb Al}_2(\text{SO}_4)_3} \left| \frac{1 \text{ lb mol Al}_2(\text{SO}_4)_3}{342.1 \text{ lb Al}_2(\text{SO}_4)_3} \right| \left| \frac{1 \text{ lb mol Al}_2\text{O}_3}{1 \text{ lb mol Al}_2(\text{SO}_4)_3} \right|$$

$$\frac{101.9 \text{ lb Al}_2\text{O}_3}{1 \text{ lb mol Al}_2\text{O}_3} \left| \frac{1 \text{ lb bauxite}}{0.554 \text{ lb Al}_2\text{O}_3} \right| = 1075 \text{ lb bauxite}$$

$$1075$$

Solutions Chapter 9

9.21 Basis: 100 kg of fusion mass



Comp.	Wt.% = kg	MW	kg mol
BaSO ₄	11.1	233.3	0.0476
BaS	72.8	169.3	0.430
C	13.9	12.0	1.16
Ash	2.2	—	—
	100.0	—	—

$$\text{BaSO}_{4 \text{ orig.}} = 0.0476 + 0.430 = 0.4776 \text{ mol}$$

$$\text{C}_{\text{orig.}} = 1.16 + 4(0.430) = 2.88 \text{ mol} \quad \text{Carbon is the limiting reactant.}$$

$$\text{Needed C for complete reaction} = 4(0.4776) = 1.9104 \text{ mol}$$

$$\% \text{ excess} = \frac{2.88 - 1.91}{1.91} \times 100 = \boxed{50.8\% \text{ excess C}}$$

$$\text{Degree of completion} = \frac{0.4776 - 0.0476}{0.4776} = \boxed{0.900}$$

You could calculate the extent of reaction from the BaSO₄, and use it to get the original amounts of reactants.

Solutions Chapter 9

9.22 $\text{CO} + \text{Cl}_2 \rightarrow \text{COCl}_2$

Basis: 20 kg products

Comp.	kg	mol wt.	kg mol	kg mol	kg mol
			<u>mol</u>	<u>Cl₂ in</u>	<u>CO in</u>
Cl ₂	3.00	70.91	0.0423	0.0423	
COCl ₂	10.00	98.91	0.1011	0.1011	0.1011
CO	<u>7.00</u>	<u>28.01</u>	<u>0.250</u>	<u>0.393</u>	<u>0.250</u>
	20.00			0.143	0.351

The extent of reaction is

$$\text{CO: } \frac{0 - 0.351}{-1} = 0.351$$

$$\text{Cl}_2: \frac{0 - 0.143}{-1} = 0.143 \text{ (smallest } \xi \text{)}$$

Cl₂ is the limiting reactant; CO is the excess reactant

$$\text{a. } \frac{0.351 - 0.143}{0.143} (100) = \boxed{145\% \text{ excess CO}}$$

$$\text{b. } \frac{0.1011}{0.143} (100) = \boxed{70.7\% \text{ Cl}_2 \text{ converted}}$$

$$\text{c. } \frac{0.1011 \text{ kg mol COCl}_2}{(0.143 + 0.351) \text{ kg mol reactants}} = \boxed{0.205}$$

Solutions Chapter 9

9.23 Step 4:

The molecular weights needed to solve the problem and the gram moles forming the basis are:

Component	kg	Mol. wt.	g mol
Sb_2S_3	0.600	339.7	1.766
Fe	0.250	55.85	4.476
Sb	0.200	121.8	1.642
FeS		87.91	

The process is illustrated in Fig. P9.19

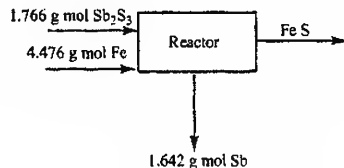


Figure P9.19

Step 5: Basis: Data given in problem statement

Steps 6-9:

(a) To find the limiting reactant, we examine the chemical reaction equation. The ratio of Sb_2S_3 to Fe in the equation is $1/3 = 0.33$. In the actual reaction the corresponding ratio is $1.766/4.476 = 0.395$, hence Sb_2S_3 is the excess reactant and Fe is the limiting reactant. The Sb_2S_3 required to react with the limiting reactant is $4.476/3 = 1.492$ g mol.

(b) The percentage of excess reactant is

$$\% \text{ excess} = \frac{1.766 - 1.492}{1.492} (100) = \boxed{18.4\% \text{ excess } \text{Sb}_2\text{S}_3}$$

Solutions Chapter 9

(c) Although Fe is the limiting reactant, not all the limiting reactant reacts. We can compute from the 1.64 g mol of Sb how much Fe actually does react:

$$\frac{1.64 \text{ g mol Sb}}{2 \text{ g mol Sb}} \left| \frac{3 \text{ g mol Fe}}{2 \text{ g mol Sb}} \right| = 2.46 \text{ g mol Fe}$$

If by the fractional degree of completion is meant the fraction conversion of Fe to products, then

$$\text{Fractional degree of completion} = \frac{2.46}{4.48} = \boxed{0.55}$$

(d) Let us assume that the percent conversion refers to the Sb_2S_3 since the reference compound is not specified in the question posed.

$$\frac{1.64 \text{ g mol Sb}}{2 \text{ g mol Sb}} \left| \frac{1 \text{ g mol } \text{Sb}_2\text{S}_3}{2 \text{ g mol Sb}} \right| = 0.82 \text{ g mol } \text{Sb}_2\text{S}_3$$

$$\% \text{ conversion of } \text{Sb}_2\text{S}_3 \text{ to Sb} = \frac{0.82}{1.77} (100) = \boxed{46.3\%}$$

(e) The yield will be stated as kilograms of Sb formed per kilogram of Sb_2S_3 that was fed to the reaction

$$\text{Yield} = \frac{0.200 \text{ kg Sb}}{0.600 \text{ kg } \text{Sb}_2\text{S}_3} = \boxed{\frac{0.33 \text{ kg Sb}}{1 \text{ kg } \text{Sb}_2\text{S}_3}}$$

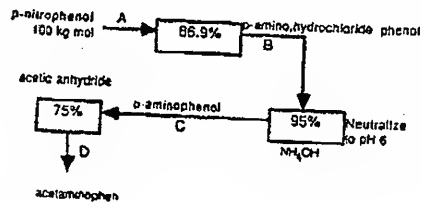
Solutions Chapter 9

9.24 Amount of o-n hydrolized: $\frac{0.10 \text{ m mol} | 1000 \mu \text{ mol}}{1 \text{ m mol}} = 100 \mu \text{ mol}$

Total protein: $\frac{1.00 \text{ mg} | 0.10 \text{ mL}}{1 \text{ mL}} = 0.100 \text{ mg}$

Specific activity = $\frac{100 \mu \text{ mol}}{(5 \text{ min})(0.10 \text{ mg protein})} = 200 \mu \text{ mol}/(\text{min})(\text{mg protein})$

9.25



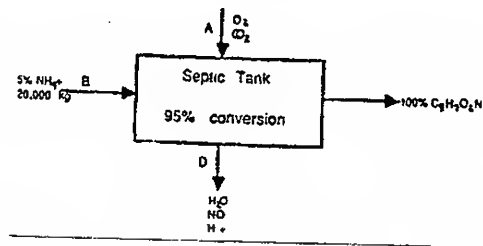
Basis: 100 kg mol A

$$\frac{100 \text{ kg mol } C_6H_5NO_2}{100 \text{ kg mol } C_6H_5NO_2} \left| \frac{86.9 \text{ kg mol } C_6H_5NOCl}{100 \text{ kg mol } C_6H_5NO_2} \right| \left| \frac{0.95 \text{ kg mol } C_6H_7NO}{1 \text{ kg mol } C_6H_5NOCl} \right| \left| \frac{3 \text{ kg mol } C_6H_5NO_2}{4 \text{ kg mol } C_6H_7NO} \right|$$

→ 0.619 fraction overall conversion

Solutions Chapter 9

9.26



$$C_5 \quad 60$$

$$H_7 \quad 7$$

$$O_2 \quad 32$$

$$N \quad 14$$

$$113 \text{ kg/k mol}$$



$$N \quad 14$$

$$H_4 \quad 4$$

$$18$$

$$\frac{20,000 \text{ kg C} | 5 \text{ kg } NH_4^+}{100 \text{ kg C}} = 1000 \text{ kg } NH_4^+$$

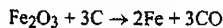
$$\frac{1000 \text{ kg } NH_4^+}{18 \text{ kg } NH_4^+} | \frac{\text{kg mol } NH_4^+}{\text{kg mol } NH_4^+} = 55.556 \text{ k mol } NH_4^+$$

$$\frac{55.556 \text{ kg mol } NH_4^+}{55 \text{ kg mol } NH_4^+} | \frac{1 \text{ kg mol } C_5H_7O_2N}{100 \text{ kg mol fed}} | \frac{95 \text{ kg mol } NH_4^+}{100 \text{ kg mol fed}} | \frac{113 \text{ kg } C_5H_7O_2N}{\text{kg mol } C_5H_7O_2N}$$

$$= 108.43 \text{ kg } C_5H_7O_2N$$

Solutions Chapter 9

9.27 Reaction on which to base excess is

Basis: 1 ton Fe_2O_3

a. Theoretical C =

$$\frac{1 \text{ ton Fe}_2\text{O}_3}{1 \text{ ton Fe}_2\text{O}_3} \times \frac{2000 \text{ lb Fe}_2\text{O}_3}{159.7 \text{ lb Fe}_2\text{O}_3} \times \frac{1 \text{ lb mol Fe}_2\text{O}_3}{1 \text{ lb mol Fe}_2\text{O}_3} \times \frac{3 \text{ lb mol C}}{1 \text{ lb mol Fe}_2\text{O}_3} \times \frac{12 \text{ lb C}}{1 \text{ lb mol C}} = 451 \text{ lb}$$

$$\frac{600 - 451}{451} \times 100 = \boxed{33\% \text{ excess C}}$$

$$\text{b. } \frac{1 \text{ ton Fe}_2\text{O}_3}{1 \text{ ton Fe}_2\text{O}_3} \times \frac{1200 \text{ lb Fe}}{55.85 \text{ lb Fe}} \times \frac{1 \text{ lb mol Fe}}{2 \text{ lb mol Fe}} \times \frac{1 \text{ lb mol Fe}_2\text{O}_3}{159.7 \text{ lb Fe}_2\text{O}_3} \times \frac{159.7 \text{ lb Fe}_2\text{O}_3}{1 \text{ lb mol Fe}_2\text{O}_3}$$

= 1720 lb Fe_2O_3 reacts

$$\frac{1720}{2000} \times 100 = \boxed{86.0\% \text{ Fe}_2\text{O}_3}$$

$$\text{c. (i) } \frac{1 \text{ ton Fe}_2\text{O}_3}{1 \text{ ton Fe}_2\text{O}_3} \times \frac{183 \text{ lb FeO}}{71.85 \text{ lb FeO}} \times \frac{1 \text{ lb mol FeO}}{2 \text{ lb mol FeO}} \times \frac{1 \text{ lb mol CO}}{1 \text{ lb mol FeO}} \times \frac{28 \text{ lb CO}}{1 \text{ lb mol CO}} = 35.62 \text{ lb CO}$$

$$\frac{1 \text{ ton Fe}_2\text{O}_3}{1 \text{ ton Fe}_2\text{O}_3} \times \frac{1200 \text{ lb Fe}}{55.85 \text{ lb Fe}} \times \frac{1 \text{ lb mol Fe}}{2 \text{ lb mol Fe}} \times \frac{3 \text{ lb mol CO}}{2 \text{ lb mol Fe}} \times \frac{28 \text{ lb CO}}{1 \text{ lb mol CO}} = 902.4 \text{ lb CO}$$

$$\text{Total (35.62 lb CO + 902.4 lb CO)} = \boxed{938 \text{ lb CO}}$$

$$\text{(ii) } \frac{1 \text{ ton Fe}_2\text{O}_3}{1 \text{ ton Fe}_2\text{O}_3} \times \frac{1200 \text{ lb Fe}}{55.85 \text{ lb Fe}} \times \frac{1 \text{ lb mol Fe}}{2 \text{ lb mol Fe}} \times \frac{3 \text{ lb mol C}}{2 \text{ lb mol Fe}} \times \frac{12 \text{ lb C}}{1 \text{ lb mol C}} = 387.1 \text{ lb C}$$

$$\frac{1 \text{ ton Fe}_2\text{O}_3}{1 \text{ ton Fe}_2\text{O}_3} \times \frac{183 \text{ lb FeO}}{71.85 \text{ lb FeO}} \times \frac{1 \text{ lb mol FeO}}{2 \text{ lb mol FeO}} \times \frac{1 \text{ lb mol C}}{1 \text{ lb mol FeO}} \times \frac{12 \text{ lb C}}{1 \text{ lb mol C}} = 15.3 \text{ lb C}$$

$$387.1 + 15.3 = \boxed{402.4 \text{ lb C used / 1 ton Fe}_2\text{O}_3}$$

Solutions Chapter 9

$$\text{d. Selectivity: Mass basis: } \frac{1200 \text{ lb Fe formed}}{183 \text{ lb FeO formed}} = 6.56$$

$$\frac{1200 \text{ lb Fe}}{55.85 \text{ lb Fe}} \times \frac{1 \text{ lb mol Fe}}{1 \text{ lb mol Fe}} = 21.49 \text{ lb mol Fe}$$

$$183 \text{ lb FeO} \times \frac{1 \text{ lb mol FeO}}{71.85 \text{ lb FeO}} = 2.55 \text{ lb mol FeO}$$

$$\text{Mole Basis: } \frac{21.49 \text{ lb mol Fe}}{2.55 \text{ lb mol FeO}} = 8.44$$

Solutions Chapter 9

9.28



MW: 71.0 40.01 58.5 74.5 18.0

Basis: 1145 lb_m NaOH + 851 lb Cl₂ ($\rightarrow$ 618 lb_m NaOCl)

a. Determine limiting reactant

Assume all Cl₂ reacts, calculate lb of NaOH required

$$\text{NaOH required} = \frac{2 \text{ lb mol NaOH}}{\text{lb mol Cl}_2} \left| \frac{\text{lb mol Cl}_2}{71 \text{ lb Cl}_2} \right| \left| \frac{851 \text{ lb Cl}_2}{1} \right| \left| \frac{40.01 \text{ lb NaOH}}{\text{lb mol NaOH}} \right|$$

= 959.11 lb NaOH required

Cl₂ is limiting reactant

or use extent of reaction

$$\text{NaOH: } \frac{1145}{40} = 28.63 \text{ lb mol} \quad (0-28.63)/-2 = 14.3$$

$$\text{Cl}_2: \frac{851}{71.0} = 11.99 \text{ lb mol} \quad (0-11.99)/-1 = 12.0 \text{ (minimum)}$$

$$\text{b. \% excess NaOH} = \frac{\text{lb mol NaOH in excess}}{\text{lb mol NaOH for rxn}} (100)$$

$$= \frac{\left(1145 \text{ lb}_m \text{ NaOH} \left(\frac{\text{lb mol NaOH}}{40.01 \text{ lb NaOH}} \right) - (959.11) \left(\frac{1}{40.01} \right) \right)}{\left(959.11 \left(\frac{1}{40.01} \right) \right)} (100)$$

$$= 19.4\% \text{ excess NaOH}$$

$$\text{c. Degree of completion} = \frac{\text{lb mol Cl}_2 \text{ that reacted}}{\text{lb mol Cl}_2 \text{ available to react}} = \frac{74.5}{851} = 0.692$$

$$\text{or } \frac{\xi}{\xi_{\text{max}}} = \frac{8.30}{12.8} = 0.69$$

(continued)

Solutions Chapter 9

$$\text{d. Yield of NaOCl} = \frac{618 \text{ lb NaOCl}}{851 \text{ lb Cl}_2} = 0.726 \frac{\text{lb}}{\text{lb}}$$

$$\text{e. } \frac{618}{745} = 8.30 \text{ lb mol NaOCl} \quad \xi = \frac{8.30 - 0}{1} = 8.30 \text{ reacting moles}$$



MW 35.45 32 71.0 18

Basis: 100 mol gas

Exit comp.	% mol	Entering moles	
		HCl	O ₂
HCl	4.4	4.4	-
Cl ₂	19.8	(2)(19.8)	-
H ₂ O	19.8	(1/2)(19.8)	9.9
O ₂	4.0	-	4.0
N ₂	52.0	-	-
	100.0	44.0	13.9

(The N₂ balance gives the O₂ as 13.8).

Calculate the extent of reaction for complete reaction

$$\text{For HCl: } \frac{0-44.0}{-4} = 11.0 \text{ (the minimum)}$$

$$\text{For O}_2: \frac{0-13.9}{-1} = 13.9$$

(a) HCl is the limiting reactant

$$\text{(b) \% excess} = \frac{139 - 44.0}{44.0} \cdot 100 = 26.36\%$$

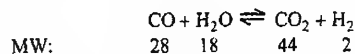
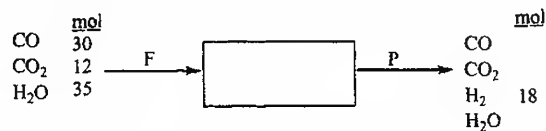
Solutions Chapter 9

$$(c) \quad \text{degree of completion} = \frac{44 - 4.4}{44} = 0.90$$

$$(\text{or } 9.9 \text{ from (d)} / 11.0) = 0.90$$

$$(d) \quad \text{extent of reaction } \xi = \frac{19.8 - 0}{2} = \text{reacting moles}$$

9.30 Basis: 30 mol CO, 12 mol CO₂, 35 mol H₂O feed = 1 hr



$$a) \quad \frac{\text{fed CO}}{\text{H}_2\text{O}} = \frac{30}{35} = 0.86 < \frac{\text{in eqn CO}}{\text{H}_2\text{O}} = \frac{1}{1} = 1$$

CO is limiting reactant

b) H₂O is the excess reactant

Solutions Chapter 9

$$c) \quad \frac{18}{35} = \boxed{0.514}$$

$$d) \quad \frac{18}{30} = \boxed{0.60} \quad (\text{for each mol of H}_2 \text{ produced, 1 mol CO reacts})$$

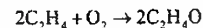
$$e) \quad \frac{18 \text{ kg mol H}_2}{1 \text{ kg mol H}_2} \left| \frac{2.016 \text{ kg H}_2}{35 \text{ kg mol H}_2\text{O}} \right| \frac{1 \text{ kg mol H}_2\text{O}}{18 \text{ kg H}_2\text{O}} = \boxed{0.0576 \text{ kg H}_2}$$

f) 1 mol of CO₂ is produced for each mol of H₂

$$\frac{18}{30} = 0.60 \frac{\text{mol CO}_2 \text{ produced}}{\text{mol CO fed}}$$

$$(g) \quad \xi = \frac{18 - 0}{1} = \boxed{18 \text{ reacting moles}} \text{ using H}_2$$

9.31



For 100% conversion of C₂H₄ according to reaction (a):

$$\frac{2 \text{ mol C}_2\text{H}_4\text{O/time}}{2 \text{ mol C}_2\text{H}_4/\text{time}} = \boxed{1}$$

For reaction b3:

$$\frac{1 \text{ mol C}_2\text{H}_4\text{O/time}}{1.33 \text{ mol C}_2\text{H}_4/\text{time}} = \boxed{0.75}$$

Solutions Chapter 9

9.32

Basis: 100 lb mesitylene (C_9H_{12})	C_9H_{12}	MW 120.1
The reactions are		
$C_9H_{12} + H_2 \rightarrow C_8H_{10} + CH_4$	C_8H_{10}	106.08
$C_8H_{10} + H_2 \rightarrow C_7H_8 + CH_4$	C_7H_8	92.06

The initial selectivity is: $C_8H_{10}/C_7H_8 = 0.7$ and 0.8

The number of moles of C_9H_{12} in the basis is

$$\frac{100 \text{ lb } C_9H_{12}}{120.1 \text{ lb } C_9H_{12}} \left| \frac{1 \text{ lb mol } C_9H_{12}}{120.1 \text{ lb } C_9H_{12}} \right| = 0.833 \text{ lb mol}$$

For the selectivity of 0.7 (the equations are in lb mol)

$$(1) C_8H_{10} + (1)C_7H_8 = 0.833$$

$$C_8H_{10}/C_7H_8 = 0.7$$

with the results:

(lb mol)	(in lb)
$C_7H_8 = 0.490$	45.1
$C_8H_{10} = 0.343$	36.4

For the selectivity of 0.8 the results are

$C_7H_8 = 0.463$	42.6
$C_8H_{10} = 0.370$	39.3

The catalyst used in the respective cases is

$$\text{Selectivity of 0.7} \quad \frac{1 \text{ lb catalyst}}{500 \text{ lb } C_7H_8} \left| \frac{0.490 \text{ lb mol } C_7H_8}{1 \text{ lb mol } C_7H_8} \right| \frac{92.06 \text{ lb } C_7H_8}{1 \text{ lb mol } C_7H_8} = 0.090 \text{ lb}$$

$$\text{Selectivity of 0.8:} \quad \frac{1 \text{ lb catalyst}}{500 \text{ lb } C_7H_8} \left| \frac{0.463 \text{ lb mol } C_7H_8}{1 \text{ lb mol } C_7H_8} \right| \frac{92.06 \text{ lb } C_7H_8}{1 \text{ lb mol } C_7H_8} = 0.085 \text{ lb}$$

Solutions Chapter 9

Income change

$$\text{Increase in } C_8H_{10}: \quad \frac{\$}{(39.3 - 36.4)(\$0.65)} = +1.89$$

$$\text{Decrease in } C_7H_8: \quad (45.1 - 42.6)(\$22) = -0.55$$

Expense change (decrease)

$$\text{Change in catalyst used: } (0.090 - 0.085)(\$25) = +0.13$$

$$\text{Net change} \quad \boxed{\$1.47}$$

10.1

Basis: 1 mol A



50 percent conversion gives as the product:

	<u>mol</u>
A	0.5
B	<u>1.5</u>
	2.0

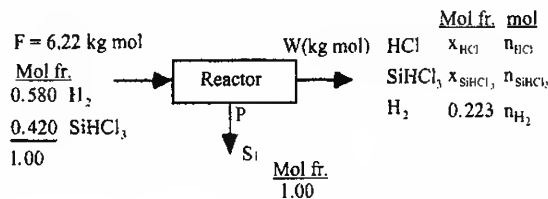
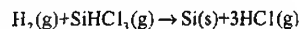
(a) Mole fraction $A = 0.5/2.0 = \boxed{0.25}$

(b) Extent of reaction $\xi = \frac{0.5 - 1.0}{-1} = \boxed{0.5 \text{ using A}}$

10.2 Assume a steady state flow process with reaction.

Step 5: Basis: 1 hr (6.22 kg mol = F)

Steps 1, 2, 3 and 4:



MW Si = 28.086

$$n_{H_2}/W = 0.223$$

Step 6: Unknowns: W, P, $3n_i$ Step 7: Balances: element balances are H, Si, Cl, $\sum n_i = W$, $n_{H_2}/W = 0.223$

Or, using the extent of reaction

Step 6: Unknowns = 6:
W, P, $3n_i, \xi$

Step 7: Balances = 6

Species balances: H_2 , $SiHCl_3$, HCl , Si

$$\sum n_i = W$$

$$n_{H_2}/W = 0.223$$

Steps 8 and 9: Balances are in kg mol.

$$Cl \text{ (kg mol): } \frac{\text{In}}{6.22(0.420)(3)} = \frac{\text{Out}}{n_{HCl} + n_{SiHCl_3}(3)}$$

$$Si \text{ (kg mol): } 6.22(0.420)(1) = P(1) + n_{SiHCl_3}$$

$$H \text{ (kg mol): } 6.22[(0.580)(2) + 0.420(1)] = n_{HCl} + n_{SiHCl_3} + n_{H_2}(2)$$

Balances using ξ :

$$H_2: [n_{H_2} - (0.580)(6.22)] = (-1)(\xi)$$

$$SiHCl_3: [n_{SiHCl_3} - (0.420)(6.22)] = (-1)(\xi)$$

$$HCl: [n_{HCl} - 0] = (+3)(\xi)$$

$$Si: [n_{Si} - 0] = (+1)(\xi)$$

$$\xi = 1.83$$

(continued)

Solutions Chapter 10

Solution: $W = 8.05$ $P = 1.83$

$$n_{H_2} = 1.78 \quad n_{HCl} = 5.49 \quad n_{SiHCl_3} = 0.7824$$

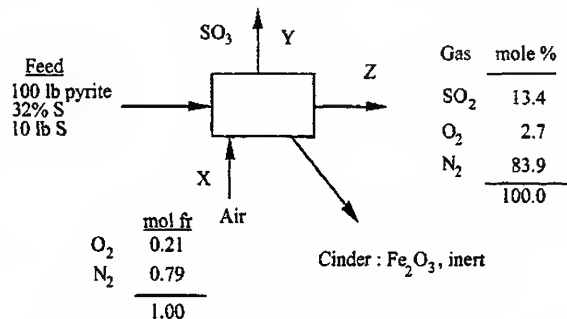
$$\frac{1.83 \text{ kg mol Si}}{1 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{20 \text{ min}}{1 \text{ kg mol Si}} \times 28.086 \text{ kg Si} = 17.13 \text{ kg Si}$$

$$\frac{1.46 \text{ kg Si initial}}{18.59 \text{ kg final Si}}$$

10.3

Step 5: Basis: 100 lb pyrites in $2 \text{ FeS}_2 + \frac{11}{2} \text{ O}_2 \rightarrow \text{Fe}_2\text{O}_3 + 4 \text{ SO}_2$

Steps 2, 3, and 4:



Let X = mol air in, Y = mol SO_3 out, Z = mol flue gas out

Steps 6 and 7:

Solutions Chapter 10

Using a reduced set of variables:

Unknowns (4): X, Y, Z , cinder

Balances (4): O, N, S, cinder

Steps 8 and 9:

1. Sulfur Balance: $(32 + 10)/32 = Y + 0.134Z$

2. O Balance: $0.21X = 1.5Y + (0.134 + 0.027)Z$

$$+ \frac{1 \text{ mol S}}{2 \text{ mol S}} \times \frac{1 \text{ mol Fe}}{2 \text{ mol Fe}} \times \frac{1 \text{ mol Fe}_2\text{O}_3}{1 \text{ mol Fe}_2\text{O}_3} \times \frac{1.5 \text{ mol O}_2}{1 \text{ mol Fe}_2\text{O}_3}$$

3. 2N Balance: $0.79X = 0.839Z$

Solve (1), (2), (3): $Y = 0.118 \text{ mol}$, $Z = 8.9 \text{ mol}$

Step 10:

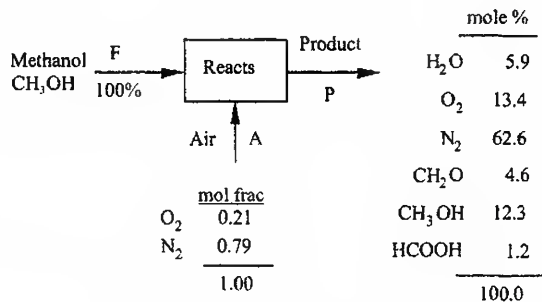
Check: $\text{mol S} = 0.118 + 0.134(8.9) = 1.31$

$$\% \text{ conversion of S to SO}_3 = (11.8)/(1.315) = \boxed{8.98\%}$$

Solutions Chapter 10

10.4

Steps 1, 2, 3 and 4:



Step 5: Basis: 100 mol P

Step 6: Unknown F, A

Step 7: Balances N, H, O, C

More balances than unknowns. Are they independent? Consistent?

Steps 8 and 9: Balances in moles

Check by first solving C, N (tie elements)

$$\text{C: } F(1) = 4.6 + 12.3 + 1.2 = 18.1 \quad F = 18.1 \text{ mol}$$

$$2\text{N: } A(0.79) = 62.6 \quad A = 79.24 \text{ mol}$$

Solutions Chapter 10

$$\text{Check via O: } (2)(79.24)(.21) + 18.1 \quad \begin{matrix} \text{A} & \text{P} \\ \text{mol} & \text{mol} \end{matrix} \quad \begin{matrix} 13.4(2) + 5.9 + 4.6 + 12.3 + 1.2(2) \\ 51.38 & 52.0 \end{matrix}$$

Close but not exactly the same, more oxygen out than in. Might be caused by round off.

$$\text{Check via H: } 4(18.1) \quad \begin{matrix} \text{A} & \text{P} \\ \text{mol} & \text{mol} \end{matrix} \quad \begin{matrix} 5.9(2) + 4.6(2) + 12.3(4) + 1.2(2) \\ 72.40 & 72.6 \end{matrix}$$

Not exactly the same; more hydrogen out than in, but again may be caused by round off.

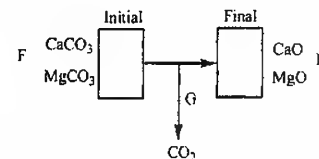
The conclusion is that probably no error exists in the measurements.

10.5

1. Additional information was the molecular weights of the compounds and the chemical reaction equations.

$$\text{MW CaCO}_3 = 100.0, \text{MW MgCO}_3 = 84.3, \text{MW CO}_2 = 44.$$

2. Assume a batch process



3. Basis: 1 g sample

4. $F = 1.000 \text{ g}$; P is not explicitly given but can be calculated: $P = 0.550 \text{ g}$; G is not explicitly given and can be calculated, $G = 0.450 \text{ g}$

5. Mass fraction of CaO in P and F , mass fraction MgO in P and F (or mass of each)

(continued)

Solutions Chapter 10

6. Species balances
7. It appears to be a carbon balance
8. 0 degrees of freedom
9. Yes

10.6

Steps 1, 2, 3, and 4: To solve this problem you must recall that CaCO_3 reacts with H_2SO_4 to form CaSO_4 and that CaCO_3 when heated yields CO_2 and CaO whereas when CaSO_4 is heated at the same time it does not decompose. Although the problem seems to be underspecified, when you draw a diagram of the process and place the known data on it, the situation becomes clearer. Assume the process is a steady state open one with reaction. Then the element balances are just $\text{in} = \text{out}$. If you use the extent of reaction, you make species balances.

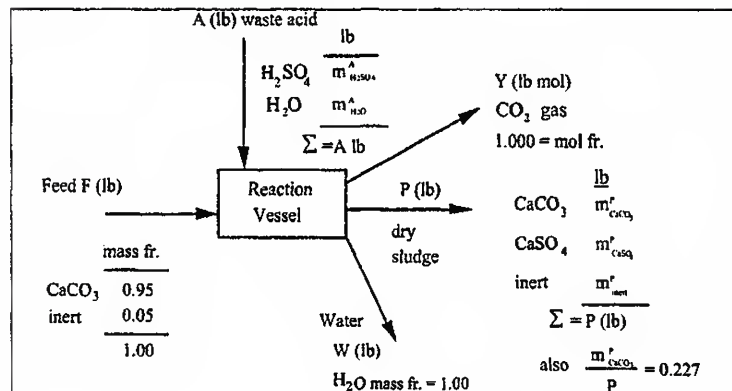
Note that we have designated the composition of P and A in terms of the mass of each component, m_i^P , rather than the mass fraction ω_i^P , because this choice makes the element or species balances linear (avoids products such as ωP).

The CO_2 liberated from the sludge is equivalent to

$$\frac{1 \text{ lb CO}_2}{10 \text{ lb P}} \left| \frac{1 \text{ lb mol CO}_2}{44 \text{ lb CO}_2} \right| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb mol CO}_2} \left| \frac{100.09 \text{ lb CaCO}_3}{1 \text{ lb mol CaCO}_3} \right|$$

$$= 0.227 \text{ lb CaCO}_3/\text{lb P}$$

Solutions Chapter 10



Step 5: Basis: $F = 100 \text{ lb}$

Step 6: The variables whose values are unknown are A , $m_{\text{H}_2\text{SO}_4}^A$, $m_{\text{H}_2\text{O}}^A$, $m_{\text{CaCO}_3}^P$, $m_{\text{CaSO}_4}^P$, m_{inert}^P , P , W , and Y , a total of 9.

Step 7: The element balances that can be made are Ca, C, O, S, H, inert (6 total) and we know $\sum m_i^A = A$, $\sum m_i^P = P$, and $(m_{\text{CaCO}_3}^P / P) = 0.227$ for a total of 9. If the equations are independent, we can find a unique solution.

Steps 8 and 9: The equations ($\text{in} = \text{out}$) are (except for the inert balance which is in lb) in moles

(continued)

Solutions Chapter 10

$$\text{Ca: } \frac{95 \text{ lb CaCO}_3}{100.09 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb mol CaCO}_3} \right| \frac{1 \text{ lb mol Ca}}{1 \text{ lb mol CaCO}_3}$$

$$= \frac{m_{\text{CaCO}_3}^p \text{ lb CaCO}_3}{100.09 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb mol CaCO}_3} \right| \frac{1 \text{ lb mol Ca}}{1 \text{ lb mol CaCO}_3}$$

$$+ \frac{m_{\text{CaSO}_4}^p \text{ lb CaSO}_4}{136.15 \text{ lb CaSO}_4} \left| \frac{1 \text{ lb mol CaSO}_4}{1 \text{ lb mol CaSO}_4} \right| \frac{1 \text{ lb mol Ca}}{1 \text{ lb mol CaSO}_4}$$

$$\text{C: } \frac{0.95 \text{ lb CaCO}_3}{100.09 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb mol CaCO}_3} \right| \frac{1 \text{ lb mol C}}{1 \text{ lb mol CaCO}_3} = \frac{Y \text{ lb mol CO}_2}{1 \text{ lb mol CO}_2} \left| \frac{1 \text{ lb mol C}}{1 \text{ lb mol CO}_2} \right|$$

$$+ \frac{m_{\text{CaCO}_3}^p \text{ lb CaCO}_3}{100.09 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb mol CaCO}_3} \right| \frac{1 \text{ lb mol C}}{1 \text{ lb mol CaCO}_3}$$

$$\text{S: } \frac{m_{\text{H}_2\text{SO}_4}^A \text{ lb H}_2\text{SO}_4}{98.08 \text{ lb H}_2\text{SO}_4} \left| \frac{1 \text{ lb mol H}_2\text{SO}_4}{1 \text{ lb mol H}_2\text{SO}_4} \right| \frac{1 \text{ lb mol S}}{1 \text{ lb mol H}_2\text{SO}_4}$$

$$= \frac{m_{\text{CaSO}_4}^p \text{ lb CaSO}_4}{136.25 \text{ lb CaSO}_4} \left| \frac{1 \text{ lb mol CaSO}_4}{1 \text{ lb mol CaSO}_4} \right| \frac{1 \text{ lb mol S}}{1 \text{ lb mol CaSO}_4}$$

$$2\text{H: } \frac{m_{\text{H}_2\text{SO}_4}^A \text{ lb H}_2\text{SO}_4}{98.08 \text{ lb H}_2\text{SO}_4} \left| \frac{1 \text{ lb mol H}_2\text{SO}_4}{1 \text{ lb mol H}_2\text{SO}_4} \right| \frac{1 \text{ lb mol H}_2}{1 \text{ lb mol H}_2\text{SO}_4}$$

$$+ \frac{m_{\text{H}_2\text{O}}^A \text{ lb H}_2\text{O}}{18.016 \text{ lb H}_2\text{O}} \left| \frac{1 \text{ lb mol H}_2\text{O}}{1 \text{ lb mol H}_2\text{O}} \right| \frac{1 \text{ lb mol H}_2}{1 \text{ lb mol H}_2\text{O}}$$

$$= \frac{W \text{ lb H}_2\text{O}}{18.016 \text{ lb H}_2\text{O}} \left| \frac{1 \text{ lb mol H}_2\text{O}}{1 \text{ lb mol H}_2\text{O}} \right| \frac{1 \text{ lb mol H}_2}{1 \text{ lb mol H}_2\text{O}}$$

$$\text{O: } \frac{95 \text{ lb mol CaCO}_3}{100.09 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb mol CaCO}_3} \right| \frac{3 \text{ lb mol O}}{1 \text{ lb mol CaCO}_3}$$

$$+ \frac{m_{\text{H}_2\text{SO}_4}^A \text{ lb H}_2\text{SO}_4}{98.08 \text{ lb H}_2\text{SO}_4} \left| \frac{1 \text{ lb mol H}_2\text{SO}_4}{1 \text{ lb mol H}_2\text{SO}_4} \right| \frac{4 \text{ lb mol O}}{1 \text{ lb mol H}_2\text{SO}_4}$$

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$$+ \frac{m_{\text{H}_2\text{O}}^A \text{ lb H}_2\text{O}}{18.016 \text{ lb H}_2\text{O}} \left| \frac{1 \text{ lb mol H}_2\text{O}}{1 \text{ lb mol H}_2\text{O}} \right| \frac{1 \text{ lb mol O}}{1 \text{ lb mol H}_2\text{O}}$$

$$= \frac{Y \text{ lb mol CO}_2}{1 \text{ mol CO}_2} \left| \frac{2 \text{ lb mol O}}{1 \text{ mol CO}_2} \right|$$

$$+ \frac{m_{\text{CaCO}_3}^p \text{ lb CaCO}_3}{100.09 \text{ lb CaCO}_3} \left| \frac{1 \text{ lb mol CaCO}_3}{1 \text{ lb mol CaCO}_3} \right| \frac{3 \text{ lb mol O}}{1 \text{ lb mol CaCO}_3}$$

$$+ \frac{m_{\text{CaSO}_4}^p \text{ lb CaSO}_4}{136.15 \text{ lb CaSO}_4} \left| \frac{1 \text{ lb mol CaSO}_4}{1 \text{ lb mol CaSO}_4} \right| \frac{4 \text{ lb mol O}}{1 \text{ lb mol CaSO}_4}$$

$$+ \frac{W \text{ lb H}_2\text{O}}{18.016 \text{ lb H}_2\text{O}} \left| \frac{1 \text{ lb mol H}_2\text{O}}{1 \text{ lb mol H}_2\text{O}} \right| \frac{1 \text{ lb mol O}}{1 \text{ lb mol H}_2\text{O}}$$

$$\text{Inert: } 5 \text{ lb inert} = m_{\text{inert}}^p \text{ lb inert}$$

The solution of these equations using a computer code would give all of the values of the unknown quantities. However, a review of the set of equations, after having gone into great detail about each equation, indicates that only 4 of the equations have to be solved to get the desired answer, namely the Ca balance, the $\Sigma m_i^p = P$, and the inert balance plus $m_{\text{CaCO}_3}^p = 0.227$:

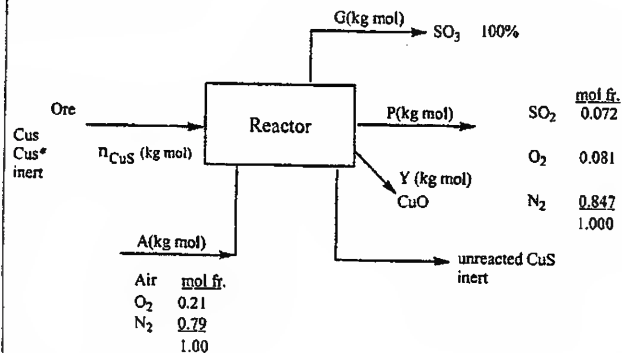
$$\Sigma m_i^p = P: \quad m_{\text{CaCO}_3}^p + m_{\text{CaSO}_4}^p + 5 = P = m_{\text{CaCO}_3}^p / 0.227$$

$$\text{Ca: } \quad 0.949 = 0.010 m_{\text{CaCO}_3}^p + 0.00734 m_{\text{CaSO}_4}^p$$

$$m_{\text{CaCO}_3}^p = 28.55 \text{ lb and } 100 \frac{28.55}{95} = 30\% \text{ unreacted.}$$

10.7

Steps 1, 2, 3, and 4:



*This CuS doesn't react.

This is a steady state open process with reaction.

Step 5: Basis: 100 kg mol P

Steps 6 and 7: Unknowns: n_{CuS} , A, G, Y
 Element balances: S, O, N, Cu

Steps 8 and 9: Balances are in kg mol on the elements

$$\text{S: } n_{\text{CuS}}(1) = G(1) + 0.072(100)$$

$$2\text{O: } A(0.21) = G(1.5) + 100(0.072) + 100(0.081) + Y\left(\frac{1}{2}\right)$$

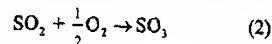
$$2\text{N: } A(0.79) = 100(0.847)$$

$$\text{Cu: } n_{\text{CuS}}(1) = Y(1)$$

Solution yields (in kg mol): $G = 1.81$, $n_{\text{CuS}} = Y = 9.01$

$$\frac{1.81 \text{ mol SO}_3}{9.01 \text{ mol CuS that reacts}} \times \frac{1 \text{ mol S}}{1 \text{ mol SO}_3} = 0.20 \text{ of CuS that reacts goes to SO}_3 \text{ [20\%]}$$

If you use the extent of reaction, you need to write down the balanced reactions



Steps 6 and 7:

The unknowns: 4 above plus ξ_1 and ξ_2

Balance: 6 species balances

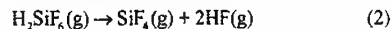
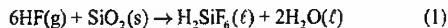
Steps 8 and 9:

CuO:	Y	=	$0 + (1)(\xi_1)$
CuS	0	=	$n_{\text{CuS}} + (-1)(\xi_1)$
O ₂ :	$P(0.081)$	=	$A(0.21) + (-1)(\xi_1) + (-\frac{1}{2})(\xi_2)$
N ₂	$P(0.847)$	=	$A(0.79)$
SO ₂	$P(0.072)$	=	$0 + (1)(\xi_1) + (-1)(\xi_2)$
SO ₃ :	G	=	$0 + (1)(\xi_2)$

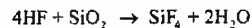
$$\xi_1 = 9.01 \quad \xi_2 = 1.81$$

Solutions Chapter 10

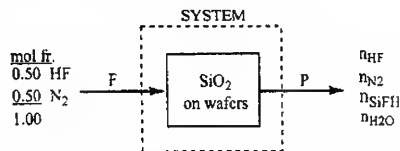
10.8



The net reaction is



Steps 2, 3, and 4:



The process is an unsteady state, open process

Step 5: Basis: 1 mol F entering

Steps 6 and 7:

Unknowns: 4 n_i , P , ξ , loss SiO_2 from wafer (L)

Balances: HF, N_2 , SiF_4 , H_2O , SiO_2 (5 species)

Other equations: $\sum n_i = P$; 10% HF reacts

Steps 8 and 9:

$$\text{HF: } n_{\text{HF}} = 0.50 + (-4)\xi = 0.50(0.90) = 0.45$$

$$\xi = 1.25 \times 10^{-2} \text{ reacting moles}$$

$$\text{SiF}_4: n_{\text{SiF}_4} = 0 + (1)(1.25 \times 10^{-2}) = 1.25 \times 10^{-2} \text{ mol}$$

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$$\text{H}_2\text{O: } n_{\text{H}_2\text{O}} = 0 + (2)(1.25 \times 10^{-2}) = 2.50 \times 10^{-2} \text{ mol}$$

$$\text{N}_2: n_{\text{N}_2} = 0.50 \text{ mol}$$

$$\text{SiO}_2: n_{\text{SiO}_2, f} - n_{\text{SiO}_2, i} = (-1)(\xi) = -1.25 \times 10^{-2} \text{ mol}$$

Composition	mol	mol fr.
HF	0.45	0.456
SiF ₄	1.25×10^{-2}	0.013
H ₂ O	2.50×10^{-2}	0.025
N ₂	0.50	0.506
	0.9875	1.000

If you use element balances:

Step 6 and 7:

The unknowns: 4 n_i , P , L

The balances: H, F, Si, O, N (presumably 4 are independent)

Other equations: $\sum n_i = P$, 10% HF reacts

Steps 8 and 9:

$$\text{H: } 0.50(1) = n_{\text{HF}} + 2n_{\text{H}_2\text{O}}$$

$$\text{F: } 0.50(1) = n_{\text{HF}} + 4n_{\text{SiF}_4}$$

$$\text{Si: } (n_{\text{SiO}_2, f} - n_{\text{SiO}_2, i}) = n_{\text{SiF}_4}$$

$$\text{O: } 2(n_{\text{SiO}_2, f} - n_{\text{SiO}_2, i}) = n_{\text{H}_2\text{O}}$$

$$\text{N: } 2(0.50) = 2n_{\text{N}_2}$$

$$n_{\text{HF}} = 0.90(0.50) = 0.45$$

10.9

We will view this process as a steady state process in an open system with flow in and out, and a change in the material in the vessel from the initial to the final states. For component i, Equation (10.1) becomes Equation (10.6)

$$n_i^{\text{out}} = n_i^{\text{in}} + \sum_{j=1}^R V_j \xi_j$$

The bioorganisms do not have to be included in the solution of the problem.

Steps 1, 2, 3, and 4

Figure P10.9 is a sketch of the process.

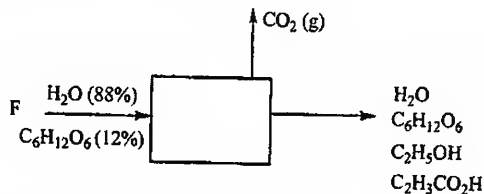


Figure P10.9

Step 5 Basis: 3500 kg F

Step 4

Convert the 3500 kg into moles of H_2O and $\text{C}_6\text{H}_{12}\text{O}_6$.

$$n_{\text{H}_2\text{O}}^{\text{initial}} = \frac{3500(0.88)}{18.02} = 170.9$$

$$n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{initial}} = \frac{3500(0.12)}{180.1} = 2.332$$

Step 6 and 7

The degree of freedom analysis is as follows:

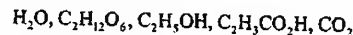
Number of variables: 9

$$n_{\text{H}_2\text{O}}^{\text{in}}, n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{in}}, n_{\text{H}_2\text{O}}^{\text{out}}, n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{out}}, n_{\text{C}_2\text{H}_5\text{OH}}^{\text{out}}, n_{\text{C}_2\text{H}_3\text{CO}_2\text{H}}^{\text{out}}, n_{\text{CO}_2}^{\text{out}}, \xi_1, \xi_2$$

Number of equations: 9

Basis: $F = 3500$ kg of initial solution (equivalent to initial moles of H_2O plus moles of sucrose)

Species material balances: 5



Specifications: 4 (3 independent)

$$n_{\text{H}_2\text{O}}^{\text{in}} = 170.4 \text{ or } n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{in}} = 2.332 \text{ (one is independent, the sum is } F \text{ in mol)}$$

$$n_{\text{C}_6\text{H}_{12}\text{O}_6}^{\text{out}} = \frac{90}{180.1} = 0.500 \quad n_{\text{CO}_2}^{\text{out}} = \frac{120}{44} = 2.727$$

The degrees of freedom are zero.

Step 8

The material balance equations, after introducing the known values for the variables are:

$$\text{H}_2\text{O}: \quad n_{\text{H}_2\text{O}}^{\text{out}} = 170.9 + (0)\xi_1 + (2)\xi_2 \quad (\text{a})$$

$$\text{C}_2\text{H}_{12}\text{O}_6: \quad 0.500 = 2.332 + (-1)\xi_1 + (-1)\xi_2 \quad (\text{b})$$

$$\text{C}_2\text{H}_5\text{OH}: \quad n_{\text{C}_2\text{H}_5\text{OH}}^{\text{out}} = 0 + 2\xi_1 + (0)\xi_2 \quad (\text{c})$$

$$\text{C}_2\text{H}_3\text{CO}_2\text{H}: \quad n_{\text{C}_2\text{H}_3\text{CO}_2\text{H}}^{\text{out}} = 0 + (0)\xi_1 + (2)\xi_2 \quad (\text{d}) \quad (\text{continued})$$

Solutions Chapter 10

$$\text{CO}_2 \quad 2.727 = 0 + (2)\xi_1 + (0)\xi_2 \quad (e)$$

If you do not use a computer to solve the equations, the sequence you should use to solve them would be

(e), plus (b), (a), (c), (d)

Step 9

The solution of Equations (a) – (e) is

$$\xi_1 = 1.364 \text{ kg moles reacting} \quad \xi_2 = 0.469 \text{ kg moles reacting}$$

Species	Results	Conversion to mass percent		
	kg moles	MW	kg	mass %
H ₂ O	171.8	18.01	3094.1	89.0
C ₂ H ₅ OH	2.727	46.05	125.6	3.6
C ₂ H ₃ CO ₂ H	0.939	72.03	67.5	1.9
CO ₂	2.272	44.0	100.0	2.9
C ₂ H ₁₂ O ₅	0.500	180.1	<u>90.1</u>	<u>2.6</u>
			3477.3	1.00

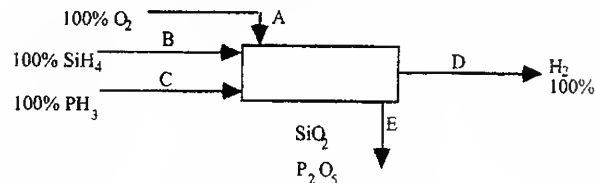
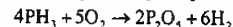
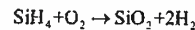
Step 10

The total mass of 3477 kg is close enough to 3500 kg of feed to validate the results of the calculations.

Solutions Chapter 10

10.10

Steps 1, 2, 3 and 4:



Step 5: Basis: 1 g mol PH₃

Step 6: No. Unknowns: A, B, D, E, $n_{\text{P}_2\text{O}_5}^E$ (5)

Step 7: Element balances: Si, H, P, O, $\omega_{\text{H}_2\text{O}}^E$ (5)

Note: $n_{\text{P}_2\text{O}_5}^F + n_{\text{SiO}_2}^E = E$

Steps 8 and 9:

<u>P Bal (in grams):</u>	<u>in</u>	<u>Out</u>
$\frac{1 \text{ g mol PH}_3}{4 \text{ g mol PH}_3} \left\{ \frac{2 \text{ g mol P}_2\text{O}_5}{1 \text{ g mol P}_2\text{O}_5} \right\} \left\{ \frac{2 \text{ g mol P}}{1 \text{ mol P}} \right\} = 3 \text{ g P}$		} in P ₂ O ₅
$\frac{1 \text{ g mol PH}_3}{4 \text{ g mol PH}_3} \left\{ \frac{2 \text{ g mol P}_2\text{O}_5}{1 \text{ g mol P}_2\text{O}_5} \right\} \left\{ \frac{5 \text{ g mol O}}{1 \text{ g mol O}} \right\} = 16 \text{ g O}$		
Total:		71 g P ₂ O ₅

(continued)

or since all the P is in stream E: $\frac{1 \text{ g mol PH}_3}{4 \text{ g mol PH}_3} \left| \frac{2 \text{ g mol P}_2\text{O}_5}{1 \text{ g mol P}_2\text{O}_5} \right| \frac{142 \text{ g P}_2\text{O}_5}{1 \text{ g mol P}_2\text{O}_5} = 71 \text{ g P}_2\text{O}_5$

Si Bal:

$$\frac{\text{Bg mol SiH}_4}{1 \text{ g mol SiH}_4} \left| \frac{\text{in}}{1 \text{ g mol SiO}_2} \right| \frac{1 \text{ g mol Si}}{1 \text{ g mol SiO}_2} \left| \frac{\text{Out}}{28.1 \text{ g Si}} \right| \frac{1 \text{ g mol Si}}{1 \text{ g mol Si}} = 28.1 \text{ B g Si}$$

$$\frac{\text{Bg mol SiH}_4}{1 \text{ g mol SiH}_4} \left| \frac{1 \text{ g mol SiO}_2}{1 \text{ g mol SiH}_4} \right| \frac{2 \text{ g mol O}}{1 \text{ g mol SiO}_2} \left| \frac{16 \text{ g O}}{1 \text{ g mol O}} \right| = 32 \text{ B g O}$$

$$\frac{71}{71 + 60.1 \text{ B}} = 0.05 \quad \text{Total:} \quad 3.55 + 3.0058 \text{ B} = 71 \quad \frac{60.1 \text{ B g SiO}_2}{\text{B} = 23.5 \text{ g mol}}$$

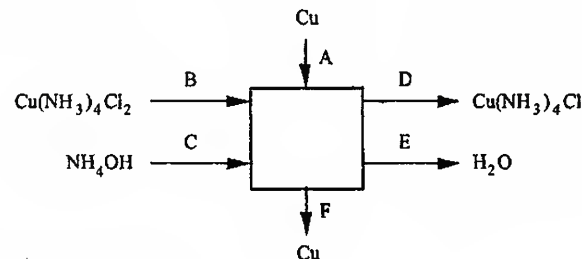
$$\frac{1 \text{ g mol PH}_3}{1 \text{ g mol PH}_3} \left| \frac{34 \text{ g PH}_3}{1 \text{ g mol PH}_3} \right| = 34 \text{ g PH}_3$$

$$\frac{23.5 \text{ g mol SiO}_2}{1 \text{ g mol SiH}_4} \left| \frac{32.1 \text{ g SiH}_4}{1 \text{ g mol SiH}_4} \right| = 7.54 \text{ g SiO}_2$$

$$\frac{754}{34} = 22.2 \frac{\text{g SiO}_2}{\text{g PH}}$$

10.11

Steps 1, 2, 3 and 4:



Step 5: Basis: 1 board

$$\text{A: Cu foil} \frac{4 \text{ in}}{8 \text{ in}} \left| \frac{0.03 \text{ in}}{(2.54 \text{ cm})^3} \right| \frac{8.96 \text{ g}}{\text{cm}^3} \left| \frac{1 \text{ g mol Cu}}{63.55 \text{ g Cu}} \right| = 2.219 \text{ g mol Cu}$$

$$\text{F: Cu remaining} \frac{1 - 0.75}{1} \left| \frac{2.219 \text{ g mol Cu}}{1} \right| = 0.555 \text{ g mol Cu}$$

Steps 6 and 7: Unknowns: B, C, D, E

Balances: Cu, N, Cl, H, O should be enough if one is redundant

Steps 8 and 9: (Balances to be solved:)

Cu Balance:

(continued)

Solutions Chapter 10

$$2.219 \text{ g mol Cu} + \frac{B \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2} = \frac{1 \text{ g mol Cu}}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}$$

$$= 1.664 \text{ g mol Cu} + \frac{D \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}$$

Cl Balance:

$$\frac{B \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2} = \frac{2 \text{ g mol Cl}}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2} = \frac{D \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}{1 \text{ g mol Cl}}$$

N Balance:

$$\frac{B \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2} = \frac{4 \text{ g mol N}}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2} + \frac{C \text{ g mol NH}_4 \text{OH}}{1 \text{ g mol NH}_4 \text{OH}}$$

$$= \frac{D \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2} = \frac{4 \text{ g mol N}}{1 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2}$$

Solution:

Cu overall: $A + B = F + D \rightarrow A + B = F + (2B)$

$$2.219 + B = 0.555 + (2B)$$

$$B = 2.219 - 0.555 = 1.664 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2$$

$$\text{Cl: } D = 2B = 2(1.664) = 3.328 \text{ g mol Cu(NH}_3)_4 \text{Cl}_2$$

$$\text{N: } 4B + C = 4D$$

$$C = 4(D - B) = 4(3.328 - 1.664) = 6.656 \text{ g mol NH}_4 \text{OH}$$

MW of NH₄OH

N	14
H ₄	4
O	16
H	1

Solutions Chapter 10

$$\frac{35 \text{ g NH}_4 \text{OH}}{1 \text{ g mol}} \left| \frac{6.656 \text{ g mol}}{1 \text{ g mol}} \right| = \boxed{232.0 \text{ g NH}_4 \text{OH}}$$

Cu(NH₃)₄Cl₂

Cu 63.55

N 56.00

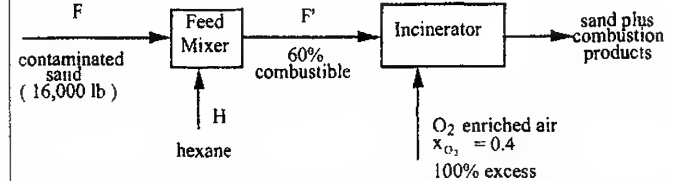
H 12.00

Cl₂ 70.90

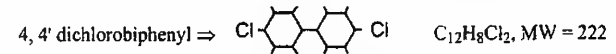
202.45

$$202.45 \text{ (g/gmol)} (1.664 \text{ g mol}) = \boxed{336.88 \text{ g Cu(NH}_3)_4 \text{Cl}_2}$$

10.12



a) Basis: 8 tons of contaminated sand containing 30% PCB



$$\frac{8 \text{ tons sand + PCB}}{1 \text{ tons sand + PCB}} \left| \frac{0.3 \text{ ton PCB}}{1 \text{ ton sand + PCB}} \right| = \frac{2000 \text{ lb PCB}}{1 \text{ ton PCB}} = 4800 \text{ lb PCB}$$

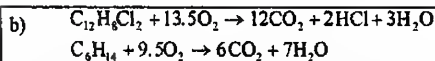
If we want the net feed to be 60% combustible, we see that the sand is a tie component:

A sand balance around the feed mixer: $16000(0.7) = F'(0.4)$ so $F' = 28,000 \text{ lb}$.

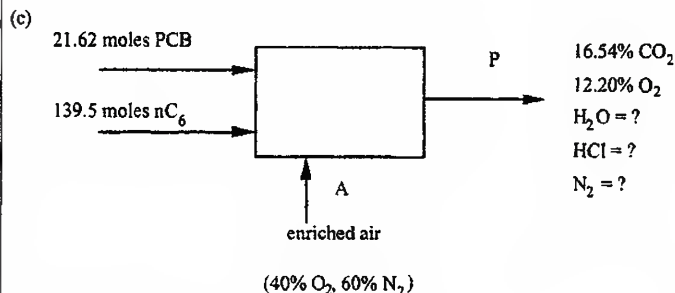
A total balance around the feed mixer: $F + H = F' \Rightarrow H = \boxed{12,000 \text{ lb}_m \text{ hexane}}$

(continued)

Solutions Chapter 10



Even with total combustion, we will produce undesirable HCl which will adversely affect the environment if it is simply vented. Therefore, it would be wise to condense the HCl and H_2O by cooling. Perhaps the acid solution might be sold to help pay for the process.



By a tie component for CO_2 , we know:

$$12(21.62) + 139.5(6) = 0.1654 P \text{ hence } P = 6629 \text{ mol}$$

By an O tie: $0.40(2)A = 0.1654(2)(6629) + 0.1220(2)(6629) + x_{H_2O}(1)(6629)$

$$x_{H_2O}(6629) = \frac{21.62 \text{ PCB Reacted} \left| \frac{3H_2O}{1 \text{ PCB}} \right| + 139.5 \text{ C}_6 \text{ Reacted} \left| \frac{7H_2O}{1 \text{ C}_6} \right|}{1} = 1042$$

$$\text{so } x_{H_2O} = 0.1572$$

From O tie balance: $A = 6065.4 \text{ mol of } 40\% O_2 \text{ air}$

Thus: $(N_2)_{in} = (N_2)_{out} = 0.6(6065.4) = 3639.2 \text{ mol } N_2$

Solutions Chapter 10

$$x_{N_2} = \frac{3639.2}{6629.0} = 0.549$$

We can get HCl by a Cl balance: $\frac{21.6 \text{ PCB Reacted} \left| \frac{2 \text{ HCl}}{1 \text{ PCB}} \right|}{1} = 43.2 \text{ mol HCl in product}$

$$x_{HCl} = 0.0065$$

Component	x_i
CO_2	0.1654
O_2	0.1220
H_2O	0.1572
HCl	0.0065
N_2	0.5490

Product
Composition

We know % excess O_2 used is : % excess = $\frac{100 [O_2 \text{ fed} - O_2 \text{ req'd}]}{(O_2 \text{ req'd})}$

$$O_2 \text{ fed} = 0.4 (\text{air fed}) = 0.4 (6065.4) = 2426.2 \text{ mol } O_2$$

Also, since we have total combustion,

$$(O_2 \text{ req'd}) = (O_2 \text{ consumed}) = (O_2 \text{ fed} - O_2 \text{ out}) = 2426.2 - 0.1220(6629)$$

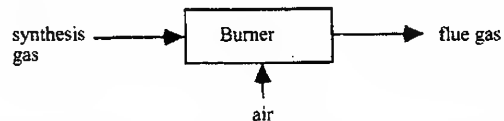
$$= 1617.5 \text{ moles req'd}$$

$$\text{Thus: } \% O_2 = 100 \left(\frac{2426.2 - 1617.5}{1617.5} \right) = \boxed{50\% \text{ excess } O_2 \text{ used}}$$

Solutions Chapter 10

10.13

Basis: 100 kg mol



One composition is unknown, the flue gas. After selection of a basis, the air flow is known.

Hence, this problem can be solved by direct addition and subtraction

Unknowns: $(\text{CO}_2, \text{H}_2\text{O}, \text{N}_2, \text{O}_2) = 4$

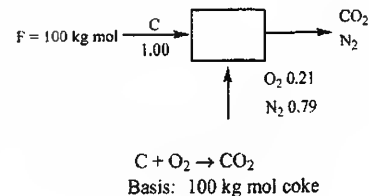
Balances: $(\text{C}, \text{H}, \text{O}, \text{N}) = 4$

Comp.	%=mol	Reaction	reqd. O_2	CO_2	H_2O	N_2	O_2
CO_2	6.4	-----	----	6.4			
O_2	0.2	-----	-(0.2)				
CO	40.0	$\text{CO} + 1/2 \text{O}_2 \rightarrow \text{CO}_2$	20.0	40.0			
H_2	50.8	$\text{H}_2 + 1/2 \text{O}_2 \rightarrow \text{H}_2\text{O}$	25.4		50.8		
N_2	2.6	-----	----			2.6	
	XS O_2 : $(0.40)(45.2) =$		<u>18.08</u>				18.08
	Total O_2 in		63.28				
	N_2 in with O_2 $(63.28)(79/21) =$					238.05	
	Totals			46.4	50.8	240.65	18.1

Solutions Chapter 10

Comp.	mol	%
CO_2	46.4	13.0
H_2O	50.8	14.3
N_2	240.65	67.6
O_2	<u>18.1</u>	<u>5.1</u>
Totals	356.0	100.0

10.14



Step 5:

a. O_2 in = 100 kg mol

$$\frac{100 \text{ kg mol C}}{1 \text{ mol C}} \left| \frac{1 \text{ mol O}_2}{1 \text{ mol C}} \right| \frac{79 \text{ mol N}_2}{21 \text{ mol O}_2} = 376 \text{ kg mol N}_2 \text{ in}$$

Steps 6 and 7:

Unknowns: moles (n_i) CO_2 , O_2 , and N_2 in P, and P

Balances: elements C, O, N

$$\text{Equations: } \sum n_i^P = P$$

or add ξ and have C, CO_2 , N_2 , O_2 species balances

(continued)

Solutions Chapter 10

Steps 8 and 9:

Element balances

$$\begin{array}{lcl}
 \text{C:} & \text{in} & \text{out} \\
 & 100 & = n_{\text{CO}_2} \\
 \text{2O:} & 100 & = n_{\text{CO}_2} + n_{\text{O}_2} \quad n_{\text{O}_2} = 0 \\
 \text{2N:} & 376 & = n_{\text{N}_2}
 \end{array}$$

Component in P	kg mol	mol %
N ₂	376	79
O ₂	0	0
CO ₂	100	21
	476	100

With 50% xs air, xsO₂, is 50 mol

The total O₂ in is 150 kg mol

The N₂ in is

$$\frac{150 \left| \frac{0.79}{0.21} \right|}{0.21} = 564$$

The N and C balance are the same but the 2O balance is

$$\begin{array}{lcl}
 \text{in} & \text{out} & \text{reacts} \\
 150 & - & n_{\text{O}_2} = 100 \quad n_{\text{O}_2} = 50
 \end{array}$$

Component in P	kg mol	mol %
N ₂	564	79
O ₂	50	7
CO ₂	100	14
	714	100

c. Same 150 mol O₂ enter and 564 mol N₂ exit but O₂ is different

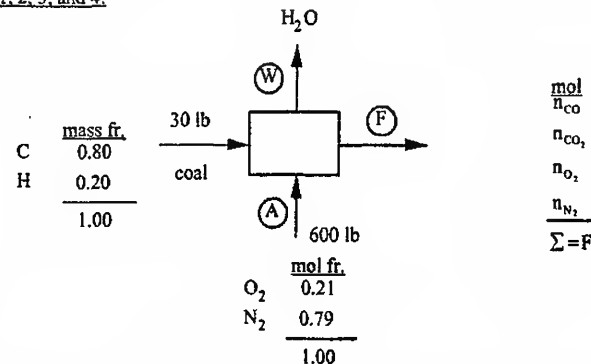
Solutions Chapter 10

$$\begin{array}{lcl}
 \text{in} & \text{mol CO}_2 \text{ used} & \text{Used CO} \\
 \text{Oxygen balance:} & 150 & - 90 & - 5 = 55 \text{ kg mol O}_2 \text{ lb fg}
 \end{array}$$

Component	kg mol	mol%
CO ₂	90	12.51
CO	10	1.39
O ₂	55	7.65
N ₂	564	78.45
Total	719	100.00

10.15

Steps 1, 2, 3, and 4:



Steps 5 and 6: With a basis of 30 lb coal, only n_{N_2} , n_{O_2} , n_{CO_2} , n_{CO} , F and W are unknown.

Total 6

(continued)

Solutions Chapter 10

Step 7: Can make C, H, O, N element balances.

$$\text{plus } \frac{n_{\text{CO}_2}}{n_{\text{CO}}} = \frac{3}{2} \text{ and } \sum n_i = F$$

Do calculations in moles, but you don't need to make all of the element balances

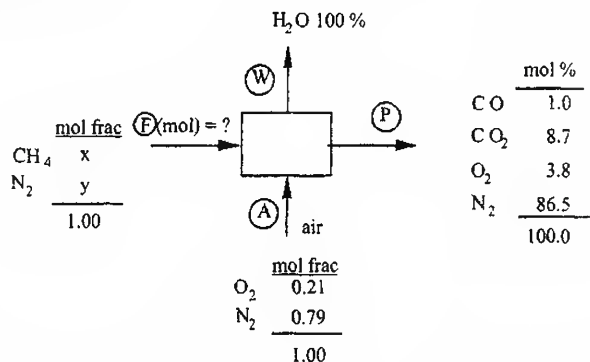
Comp.	lb	mol wt	lb mol	Rxn	reqd O ₂
C	24	12	2	C+O ₂ →CO ₂	2.0
2H	6	2	3	H ₂ +1/2O ₂ →H ₂ O	1.5
	30				3.5

$$\frac{3.5 \text{ lb mol O}_2}{0.21 \text{ lb mol O}_2} = 16.67 \text{ lb mol air reqd.}$$

$$\text{or } \frac{4.35 - 3.5}{3.5} (100) = 24.3\%$$

10.16

Steps 1, 2, 3 and 4:



Solutions Chapter 10

Step 5: Basis: 100 mol P

Step 6: Unknowns: x, y, A, W, F Total 5

A and P will be mol

Step 7: Element Balances: C, H, N, O

Equations:

a) If x and y are moles, not mole fractions,
add: $x + y = F$

b) If x, y are mole fr., add $x + y = 1.00$ Total 5

Steps 8 and 9: Use x and y as mol:

$$\text{C balance: } x = 8.7 + 1.0 = 9.7$$

$$2\text{N balance: } y + .79A = 86.5$$

$$2\text{H balance: } 2x = W = 2(9.7) = 19.4$$

$$2\text{O balance: } 0.21A = (1/2)(W + 8.7) + 1.0 + 3.8$$

$$\text{Use 2O bal: } A = \frac{9.7 + 8.7 + 0.5 + 3.8}{0.21} = 108$$

$$\text{Use 2N bal: } y = 1.10$$

$$\text{required O}_2: \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \quad (1)$$

$$(9.7)(2) = 19.4 \text{ mol}$$

$$\text{total O}_2 \text{ in: } (0.21)(108) = 22.7$$

$$\text{excess O}_2 = 22.7 - 19.4 = 3.3 \text{ mol}$$

$$\% \text{ xs air} = \% \text{ xs O}_2 = \frac{3.3}{19.4} (100)$$

(a)

$$= 17\%$$

(continued)

Solutions Chapter 10

(b) Percentage of CH_4 , N_2 : $\text{CH}_4 = \frac{9.7}{9.7 + 1.1} (100) = \underline{89.8\%}$ $\text{N}_2 = \frac{1.1}{9.7 + 1.1} (100) = \underline{10.2\%}$

Alternate solution: Use extent of reaction and species balances.
Another equation needed for CO: $\text{CH}_4 + 1.5\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2\text{O}$ (2)

Species balances to get ξ_1 and ξ_2 :

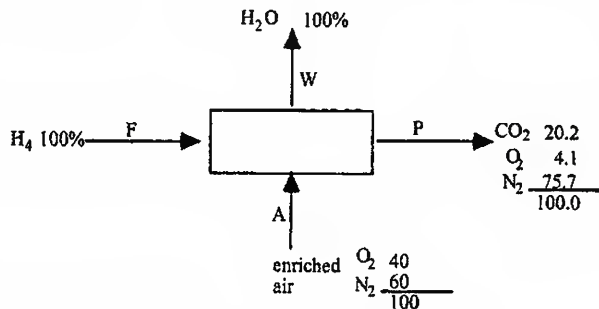
$$\text{CH}_4: \text{O} = n_{\text{CH}_4}^F + (-1)\xi_1 + (-1)\xi_2$$

$$\text{CO}_2: 8.7 = 0 + (1)\xi_1 \quad \xi_1 = 8.7 \text{ reacting moles}$$

$$\text{CO}: 1.0 = 0 + (1)\xi_2 \quad \xi_2 = 1.0 \text{ reacting moles}$$

Thus $n_{\text{CH}_4}^F = 8.7 + 1.0 = 9.7 \text{ mol}$ and other compounds follow.

10.17
Steps 1, 2, 3 and 4:



Step 5: Basis 100 mol P

Step 6: Unknowns: F, A, W (all compositions known)

(continued)

Solutions Chapter 10

Step 7: Element balances: C, H, O, N (1 extra balance)

Steps 8 and 9:

$$\text{C balance: } 20.2 = F$$

$$2\text{N balance: } 75.7 = 0.6A, A = 126.2$$

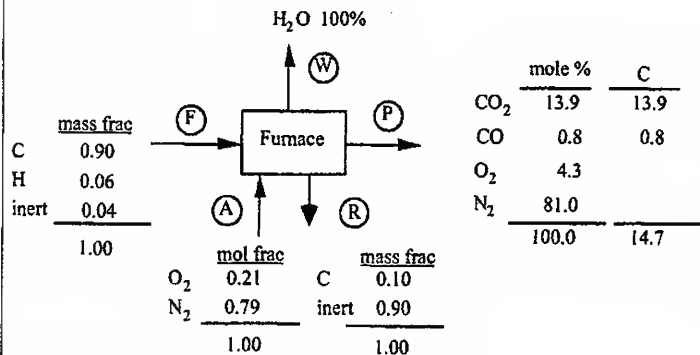
$$2\text{H balance: } 2F = W, W = 40.4$$

$$2\text{O balance: } 0.4A = 1/2 W + 20.2 + 4.1, 50.5 \neq 20.2 + 20.2 + 4.1 = 44.5$$

Analysis is not correct.

10.18

Steps 2, 3, and 4:



Step 5: Basis: 100 kg mol P

Steps 6 and 7:

Unknowns: F, R, A, W

④

(continued)

Solutions Chapter 10

Probably ok but check for redundancy

Balances: C, H, O, inert, N₂

⑤

Steps 8 and 9:Balances (in moles):

$$\text{C: } \frac{F(0.90)}{12} = P(0.139+0.008) + \frac{R(0.10)}{12} + W(0)$$

$$\text{H: } \frac{F(0.06)}{1.005} = P(0) + R(0) + W(2)$$

$$2\text{N: } A(0.79) = P(0.81) + R(0) + W(0)$$

$$2\text{O: } A(0.21) = P(0.139 + \frac{0.008}{2} + 0.043) + \frac{W}{2}$$

$$\text{Inert (mass): } F(0.04) = R(0.90)$$

$$\text{From 2N, } A = \frac{100(.81)}{0.79} = 102.53 \text{ kg mol}$$

$$\text{From 2O, } W = 5.863 \text{ kg mol}$$

$$\text{From H, } F = 196.98 \text{ kg}$$

$$\text{From inert, } R = 8.7548 \text{ kg}$$

$$\text{H in: } \frac{196.98(0.06)}{2} = 5.94$$

$$\text{O}_2 \text{ in: } \frac{5.94}{2} = 2.96$$

(continued)

Solutions Chapter 10

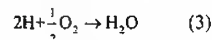
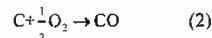
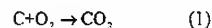
$$\text{C in} = \frac{196.98(0.90)}{12} = 14.77$$

Step 10:

$$\text{Check via C: } 196.98(0.90)/12 = 100(0.147) + (8.7548(0.10)/12) \quad \text{ok}$$

$$\text{Required O}_2: 14.7 + (5.863/2) = 17.63 \text{ kg mol} \quad \text{Total O}_2 \text{ in} = 102.53(0.21) = 21.53$$

$$\text{Excess } (21.53 - 17.63)/17.63 = 0.221 \text{ or } 22\%$$

Alternate solution using extent of reaction:

$$\text{CO}_2: n_{\text{CO}_2}^P = 13.9 = n_{\text{CO}_2}^F + (1)\xi_1 \quad \xi_1 = 13.9$$

$$\text{CO: } n_{\text{CO}}^P = 0.8 = n_{\text{CO}}^F + (1)\xi_2 \quad \xi_2 = 0.8$$

$$\text{N}_2: n_{\text{N}_2}^P = 81.0 = n_{\text{N}_2}^A \quad A = 102.5 \text{ mol}$$

$$n_{\text{O}_2}^A = 0.21(102.5) = 21.5 \text{ mol}$$

$$\text{O}_2: 4.3 = 21.5 + (-1)(\xi_1) + (-\frac{1}{2})(\xi_2) + (-\frac{1}{2})(\xi_3) \quad \xi_3 = 2.90$$

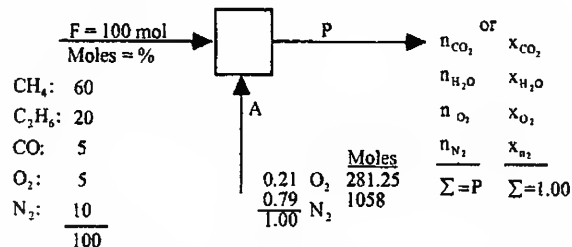
$$\text{C: } 0 = n_{\text{C}}^F + (-1)(13.9) + (-1)(0.8) \quad n_{\text{C}}^F = 14.7 \text{ mol}$$

$$\text{H: } 0 = n_{\text{H}}^F + (-2)(2.90) \quad n_{\text{H}}^F = 5.80 \text{ mol (some round off)}$$

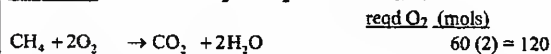
Solutions Chapter 10

10.19

Basis: 100 mol F



50% xs air: Calculate O_2 and N_2 in with the air in



Less O_2 in gas

	5.00	
Net required O_2	187.5	
xs O_2 : $187.5(.5) =$	93.75	
Total	281.25	

$\text{N}_2 \text{ in with } \text{O}_2 \quad \frac{281.25}{0.21} = 1058$

(continued)

Solutions Chapter 10

Material balances (elemental):

	in (F)	+	in (A)	=	out (P)
C:	60 + 2(20) + 5 +		0	=	n_{CO_2}
H:	60(4) + 20(6) +		0	=	$n_{\text{H}_2\text{O}}(2)$
O as O_2 :	$\frac{5}{2} + 5$	+	281.25	=	$n_{\text{CO}_2} + \frac{n_{\text{H}_2\text{O}}}{2} + n_{\text{O}_2}$
N as N_2 :	10	+	1058	=	n_{N_2}

$n_{\text{O}_2} = 288.75 - 105 - \frac{180}{2} = 93.75$

moles	composition of stack in % moles
$n_{\text{CO}_2} = 105$	7.26
$n_{\text{H}_2\text{O}} = 180$	12.44
$n_{\text{N}_2} = 1068$	73.82
$n_{\text{O}_2} = 93.75$	6.48

Total moles = 1446.75
 out 100.00

Solutions Chapter 10

10.20

mole fr				mol fr	
CH ₄	0.70	Fuel F mol Flare Flue gas P mol		CO ₂	0.0773
C ₃ H ₈	0.05			H ₂ O	0.1235
CO	0.15			O ₂	x _{O₂}
O ₂	0.05			N ₂	x _{N₂}
N ₂	0.05				1.00
	1.00				
		Air A mol Flare			
		O₂ 0.21 Air			
		N₂ 0.79 Air			
		1.00 Air			

Unknowns A, F, P, x_{O₂}, x_{N₂}, Pick F = 100 as basis

Balances: C, H, O, N (is one redundant ?) plus
0.0773 + 0.1235 + x_{O₂} + x_{N₂} = 1

Balances:

$$\text{C: } 100(0.70) + 100(0.05)(3) + 100(0.15) = P(0.0773)$$

$$\text{N}_2: 100(0.05) + 0.79A = P x_{N_2}$$

$$\text{H}_2: 100(0.70)(2) + 100(0.05)4 = P(0.1235) \text{ (redundant with C)}$$

$$\text{O}_2: 100(0.15)\frac{1}{2} + 100(0.05) + A(0.21) = P\left[(0.0773) + \frac{0.1235}{2} + x_{O_2}\right]$$

$$\Sigma x_i = 0.7992 = x_{O_2} + x_{N_2}$$

Solve C (or H₂) balance for P; P = 1294

Solve N₂, O₂ and $\Sigma x_i = 1$ simultaneously for A, x_{O₂}, x_{N₂}

(continued)

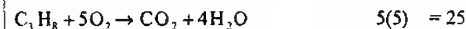
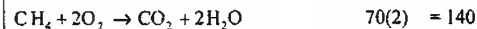
Solutions Chapter 10

A = 1203 moles

x_{O₂} = 0.0648 and x_{N₂} = 0.7344 (not needed)

Calculation of the required O₂

Required O₂



$$\text{O}_2 \text{ present in F} \quad \frac{-5.0}{167.5 \text{ reqd}}$$

$$A(0.21) = 252.54 \text{ O}_2 \text{ in}$$

$$\text{less } \frac{167.5 \text{ reqd O}_2}{85.04 \text{ xs O}_2}$$

$$\frac{85.04}{167.5} (100) = \boxed{51\%}$$

10.21

Steps 1, 2, 3, 4:

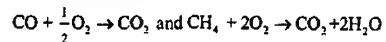
F = 100 (basis)			P		mol fr.	mol fr.	mo calculated
mol = %	O ₂ reqd		CO ₂	x			
CO 13.54	6.77		O ₂	y	0.037	8.27	
CO ₂ 15.22	--		N ₂	z	0.724	161.92	
H ₂ 15.01	7.505		H ₂ O	$\frac{1-x-y-z}{1.00}$	$\frac{0.096}{1.00}$	<u>21.41</u>	
CH ₄ 3.20	6.40						
N ₂ <u>53.03</u>	--						
100.00	20.675						
		A	0.21 O ₂				
			0.79 N ₂				
			1.00				

Step 5: Basis: 100 mol F

Step 6: Unknowns: P, x, y, z

Step 7: Balances C, H, O, N ok

Steps 8 and 9:

Air in is based on complete combustion

$$\text{xs O}_2 = 0.40 (20.675) = 8.27$$

$$\text{reqd O}_2 = \frac{20.675}{28.945}$$

$$\text{total O}_2 = 28.945$$

$$\text{N}_2 \text{ in with air } 28.945 \left(\frac{.79}{.21} \right) = 108.89 \text{ mol}$$

$$\text{Air} = \boxed{137.84 \text{ mol}}$$

Balance

$$2\text{N} \quad \text{N}_2 \text{ out} = 108.89 + 53.03 = 161.92 \text{ mol}$$

(continued)

$$\begin{aligned} \text{C} \quad \text{CO}_2 \text{ out} &= 13.54 + 15.22 + 3.20 = 31.96 \text{ mol} \\ 2\text{H} \quad \text{H}_2\text{O out} &= 15.01 + 2(3.20) = 21.41 \text{ mol} \\ 2\text{O} \quad \text{O}_2 \text{ out} &= 28.945 + \frac{13.54}{2} + 15.22 - 31.96 - \frac{21.41}{2} = 8.27 \text{ mol} \\ &(\text{as O}_2) \end{aligned}$$

Alternate solution: Use the extent of reaction and species balances

10.22

Steps 1, 2, 3 and 4:

F			P = 100 mol (Basis)		%	C	O ₂	H ₂
CH ₃ CH ₂ OH	1.00		CO ₂	0.7				
		A	O ₂	2.1			2.1	
			CO	2.3	2.3	2.3/2		
			H ₂	7.1				7.1
			CH ₄	2.6	2.6			5.2
			N ₂	<u>85.2</u>				
			100.0	5.6	3.95	12.3		

Step 5: Basis: 100 mol P

Step 6: Unknowns: F, A, B, W

Step 7: Balances: C, O, H, N ok

Steps 8 and 9:

Via algebra

$$2\text{N balance: } A(.79) = 85.2 \quad A = 107.85 \text{ mol}$$

$$\text{C balance: } F(2) = B(2) + 5.6$$

$$2\text{H balance: } F(3) = B(2) + W(1) + 12.3$$

(continued)

Solutions Chapter 10

$$2O \text{ balance: } F\left(\frac{1}{2}\right) + (.21)A = B\left(\frac{1}{2}\right) + W\left(\frac{1}{2}\right) + 3.95$$

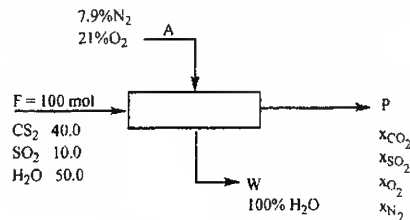
Solution: $B = 44.1 \text{ mol}$
 $F = 46.9 \text{ mol}$
 $W = 40.2 \text{ mol}$

$$\frac{44.1 \text{ mol acet.}}{100 \text{ mol P}} \left| \frac{44 \text{ kg acet.}}{1 \text{ kg mol acet.}} \right| \frac{100 \text{ mol P}}{46.9 \text{ mol EtOH}} \left| \frac{1 \text{ kg mol EtOH}}{46 \text{ kg}} \right| = \boxed{0.899} \frac{\text{kg acetaldehyde}}{\text{kg ethanol}}$$

Alternate solution: Use extent of reaction and species balances, but it is more complicated.

10.23

Steps 2, 3, and 4:

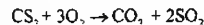


Step 5:

Basis: 100 mols feed; assume complete combustion

Step 4:

Equations:



$$\text{O}_2 \text{ required: } \frac{40 \text{ mol CS}_2}{1} \left| \frac{3 \text{ mol O}_2}{1 \text{ mol CS}_2} \right| = 120.0 \text{ mol O}_2$$

(continued)

Solutions Chapter 10

$$\% \text{ excess: } \frac{\text{O}_2 \text{ excess}}{\text{O}_2 \text{ required}} \times 100 = \% \text{ excess}$$

Steps 6, 7, 8 and 9:

5 unknowns and 5 equations $\rightarrow$ unique solution

Element balances

Component	Mol in	Mol out
C	40.0	$P x_{\text{CO}_2}$
2S	$\frac{1}{2}(10.0) + 40.0$	$\frac{1}{2}(0.02)P$
2O	$10.0 + \frac{1}{2}(50.0) + .21A$	$(x_{\text{CO}_2} + 0.02 + x_{\text{O}_2})P + \frac{1}{2}W$
2N	.79A	$(1 - x_{\text{O}_2} - 0.02 - x_{\text{CO}_2})P$
2H	50.0	W

$$P = \frac{2(45.0)}{.02} = 4500$$

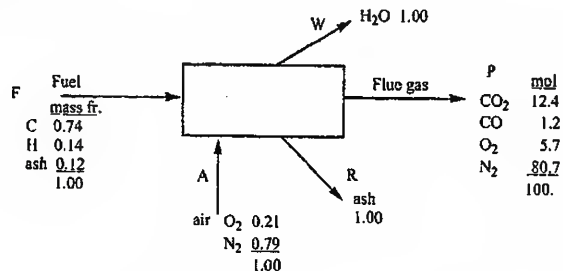
$$x_{\text{CO}_2} = 0.0089$$

$$\% \text{ Excess} = \frac{0.1829(4500 \text{ mol O}_2)}{120 \text{ mol}} (100) = \boxed{686\%}$$

Alternate solution: Use extent of reaction and species balances.

10.24

Steps 2, 3 and 4:



Step 5: Basis: P = 100 mol

Step 6: Unknowns: F, A, R, W } a discrepancy unless one

Step 7: Balances: C, H, O, N, ash } balance is not independent

Steps 8 and 9: all balances in moles

$$\text{C balance: } \frac{F(0.74)}{12} = 12.4 + 1.2 = 13.6$$

$$F = \frac{(13.6)(12)}{0.74} = 220.5 \text{ lb}$$

$$2\text{N balance: } A(0.79) = 80.7 \quad A = 102.2 \text{ mol}$$

$$2\text{H balance: } \frac{F(0.14)}{2} = W; \quad W = 15.44 \text{ mol}$$

$$2\text{O balance: } A(0.21) = W \frac{(1.00)}{2} + 12.4 + \frac{1.2}{2} + 5.7$$

(continued)

$$21.46 = 26.42 \quad \text{not equal hence}$$

Some discrepancy exists

A total balance can be used, but must be in mass, and the mass of P calculated.

10.25

Basis: 100 moles exhaust gas

Comp	exhaust gas mol	tie element	exit gas	
			%	mol
CO ₂	16.2		13.1	16.2
O ₂	4.8	83.8		
N ₂	79.0			
Total	100.0			

$$\frac{16.2 \text{ mol CO}_2}{100.0 \text{ mol exhaust gas}} \bigg| \frac{100.0 \text{ mol exit gas}}{13.1 \text{ mol CO}_2} = 123.6 \text{ mol exit gas}$$

$$\text{exhaust gas} = 100.0 \text{ mol}$$

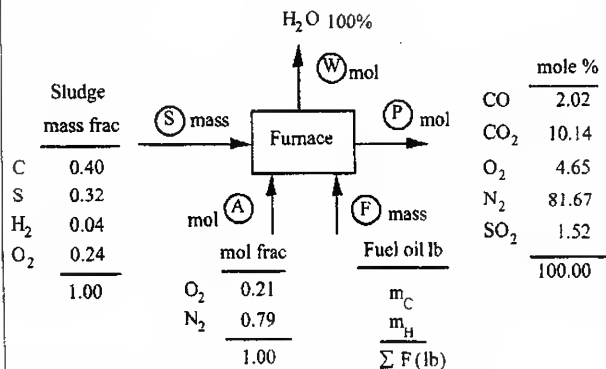
$$\text{air leaked in} = 23.6 \text{ mol}$$

$$\frac{23.6}{100.0} = 0.236 \text{ mol air / mol exhaust gas}$$

Solutions Chapter 10

10.26

Steps 2, 3, and 4:



Step 5:

Basis: 100 mol P

Steps 6 and 7:

Unknowns: S, W, F (or m_H), A, m_C ⑤ Element Balances: S, C, H, O, N

Element Balances (moles)

$$S: \frac{0.32S}{32} = 1.52 \quad S = 152 \text{ lb}$$

$$2N: A(.79) = 81.67 \quad A = 103.38 \text{ lb mol (2998.01 lb)}$$

$$C: \frac{S(0.40)}{12} + \frac{m_C}{12} = 10.14 + 2.02 \quad m_C = 85.12 \text{ lb} \quad (\text{continued})$$

Solutions Chapter 10

$$2O: \frac{0.24(152)}{32} + A(0.21) = \frac{W}{2} + 1.52 + 10.14 + 4.65 + \frac{2.02}{2}$$

$$W = 11.04 \text{ lb mol (198.71 lb)}$$

$$2H: \frac{0.04(152)}{2.03} + \frac{m_H}{2.03} = W \quad m_H = 16.32 \text{ lb}$$

Check via a total mass balance

$$152 + 16.32 + 85.12 + 2998.01 = 198.71 + 3035.56$$

$$3251.45 = 3234.27 \quad \text{close enough}$$

	lb	mass fr
C	85.12	0.84
H	16.32	0.16
	101.44	1.00

$$\frac{S}{F} = \frac{152 \text{ lb}}{101.44 \text{ lb}} = 1.50$$

← ⑤

10.27

Basis: 1 min

$$[CaO]_{\text{feed}} = \frac{1000 \text{ gal}}{\text{min}} \times \frac{\text{ft}^3}{7.48 \text{ gal}} \times \frac{1.05 \times 62.4 \text{ lb soln}}{\text{ft}^3} \times \frac{0.02 \text{ lb H}_2\text{SO}_4}{\text{lb soln}} \times \frac{\text{mol H}_2\text{SO}_4}{98 \text{ lb H}_2\text{SO}_4} \times \frac{\text{mol CaO}}{\text{mol H}_2\text{SO}_4}$$

$$\frac{56.1 \text{ lb CaO}}{\text{mol CaO}} = 100.3 \text{ lb CaO/min}$$

$$\text{Feed rate of CaO} = 1.2 [CaO]_{\text{feed}} = 120.4 \text{ lb CaO/min}$$

(continued)

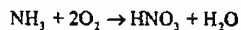
Solutions Chapter 10

$$\text{CaSO}_4 \text{ production rate} = \frac{100.3 \text{ lb CaO}}{\text{min}} \left| \frac{\text{mol CaO}}{56.1 \text{ lb CaO}} \right| \left| \frac{\text{mol CaSO}_4}{\text{mol CaO}} \right| \left| \frac{136.1 \text{ lb CaSO}_4}{\text{mol CaSO}_4} \right| \left| \frac{\text{ton}}{2000 \text{ lb}} \right|$$

$$\times \frac{60 \text{ min}}{\text{hr}} \left| \frac{24 \text{ hr}}{\text{d}} \right| \left| \frac{365 \text{ d}}{\text{yr}} \right| = 63,947 \text{ ton/yr}$$

10.28

Basis: 100 mol of product gas



The product gas from such a reactor has the following composition (water free basis):

0.8% NH_3
 9.5% HNO_3
 3.8% O_2
 85.9% N_2

Determine the percent conversion of NH_3 and the percent excess air used.

$$n_{\text{NH}_3}^{\text{out}} = n_{\text{NH}_3}^{\text{in}} + v_{\text{NH}_3} (9.5)$$

$$0.8 = n_{\text{NH}_3}^{\text{in}} + (-1)(9.5)$$

$$F = n_{\text{NH}_3}^{\text{in}} = 0.8 + 9.5 = 10.3 \text{ mol}$$

$$\frac{n^{\text{out}} - n^{\text{in}}}{v} = \xi$$

$$\text{For } \text{HNO}_3: \frac{9.5 - 0}{1} = 9.5 = \xi$$

$$\text{Percent conversion } f = (100\%) \xi / F = 92.2\%$$

(continued)

Solutions Chapter 10

Calculate the entering oxygen using a N_2 balance:

$$\text{N}_2: 0.79A = 85.9; \text{ therefore, } A = 108.73 \text{ mol}$$

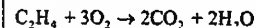
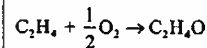
Calculate the theoretical O_2 needed for the reaction

$$(\text{O}_2)_{\text{theor}} = 2 \times 10.3 = 20.6 \text{ mol}$$

$$\text{Feed rate of } \text{O}_2 = 0.21A = 22.83 \text{ mol}$$

$$\% \text{ Excess } \text{O}_2 = [(22.83 - 20.6) / 20.6](100) = 10.84\%$$

10.29

Basis: 100 mol of product gas (20.5% $\text{C}_2\text{H}_4\text{O}$; 72.7 N_2 ; 2.3 O_2 ; and 4.5% CO_2)

$$\text{Calculate } \xi_1: \quad \xi_1 = \frac{n_i^{\text{out}} - n_i^{\text{in}}}{v_i} \quad \text{Use } \text{C}_2\text{H}_4\text{O}: \quad \xi_1 = \frac{20.5 - 0}{1} = 20.5$$

$$\text{Calculate } \xi_2: \quad \text{Use } \text{CO}_2: \quad \xi_2 = \frac{4.5 - 0}{2} = 2.25$$

Calculate the entering air using a N_2 balance:

$$\text{N}_2: 0.79A = 72.7; \text{ therefore, } A = 92.03 \text{ mol}$$

Calculate the moles of C_2H_4 entering (F)

$$n_{\text{C}_2\text{H}_4}^{\text{out}} - n_{\text{C}_2\text{H}_4}^{\text{in}} = v_1 \xi_1 + v_2 \xi_2$$

$$0 - F = -\xi_1 - \xi_2 \quad \text{hence } F = 22.75$$

(continued)

Solutions Chapter 10

$$\text{O}_2 \text{ feed rate} = 0.21A = 19.33 \text{ mol}$$

$$(\text{O}_2)_{\text{theor}} = F/2 = 11.375 \text{ mol}$$

$$\% \text{ Excess O}_2 = [(19.33 - 11.375)/11.375](100) = 70.0\%$$

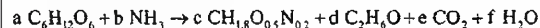
To get the ethylene feed:

$$\frac{22.75 \text{ C}_2\text{H}_4}{20.5 \text{ mol C}_2\text{H}_4\text{O}} \left| \frac{100,000 \text{ ton C}_2\text{H}_4\text{O}}{\text{yr}} \right| \frac{2000 \text{ lb C}_2\text{H}_4\text{O}}{\text{ton C}_2\text{H}_4\text{O}} \left| \frac{\text{mol C}_2\text{H}_4\text{O}}{44 \text{ lb C}_2\text{H}_4\text{O}} \right|$$

$$\times \frac{\text{yr}}{365 \text{ d}} \left| \frac{\text{d}}{24 \text{ h}} \right| \frac{28 \text{ lb C}_2\text{H}_4}{\text{mol C}_2\text{H}_4} = \boxed{16,123 \text{ lb C}_2\text{H}_4/\text{h}}$$

10.30 Assume ammonia and glucose (MW = 180.1) are fed in stoichiometric proportions.

The reaction equation has to be set up and balanced to use the value given of 60% (mole assumed) conversion of glucose.



Pick a basis of 4.6 kg of EtOH (C₂H₅O, MW = 46.07)

$$\frac{4600 \text{ g EtOH}}{46.07 \text{ g EtOH}} \left| \frac{1 \text{ g mol EtOH}}{46.07 \text{ g EtOH}} \right| = 100 \text{ g mol EtOH produced}$$

To balance the chemical reaction equation use element balances. Take a basis of $a = 1$. Assume 60% conversion of the glucose means that 1 mole of glucose produces 0.6 mol of ethanol, not that one mole of glucose produces 3 mol of ethanol.

$$\begin{aligned} \text{C:} & 6 = c + 2d + e \\ \text{H:} & 12 + 3b = 1.8c + 6d + 2f \\ \text{O:} & 6 = 0.5c + d + 2e + f \\ \text{N:} & b = 0.2c \end{aligned}$$

$$\text{Specifications } 0.60 = d$$

(continued)

Solutions Chapter 10

Results

$$\begin{aligned} a &= 1 \text{ (the basis)} & d &= 0.6 \\ b &= 0.8 & e &= 0.8 \\ c &= 4 & f &= 1.8 \end{aligned}$$

$$\frac{167 \text{ g mol C}_6\text{H}_{12}\text{O}}{1 \text{ g mol C}_6\text{H}_{12}\text{O}} \left| \frac{0.08 \text{ g mol NH}_3}{1 \text{ g mol C}_6\text{H}_{12}\text{O}} \right| = 133.6 \text{ g mol NH}_3$$

$$\frac{167 \text{ g mol C}_6\text{H}_{12}\text{O}_6}{1 \text{ g mol C}_6\text{H}_{12}\text{O}_6} \left| \frac{180.1 \text{ g C}_6\text{H}_{12}\text{O}_6}{1 \text{ g mol C}_6\text{H}_{12}\text{O}_6} \right| = 30,076 \text{ g or } 30.1 \text{ kg C}_6\text{H}_{12}\text{O}_6$$

$$\frac{133.6 \text{ g mol NH}_3}{1 \text{ g mol NH}_3} \left| \frac{17.03 \text{ g NH}_3}{1 \text{ g mol NH}_3} \right| = 2,275 \text{ g or } 2.28 \text{ kg NH}_3$$

10.31

Basis: $F = 100 \text{ lb}$ given in Example 10.9

This basis gives $P = 50 \text{ lb moles}$. Note: If the problem calculations were redone because of the stated additional reactions, the value of $P = 50$ for two significant figures would not change. Similarly, the other values of the moles in P would not change. Thus, the $\text{SO}_2 + \text{CO}_2$ is $0.154 (50) = 7.7 \text{ lb mol}$. The values of the pertinent components (for NO_x use $\text{NO}_{1.5}$) for this problem are

			<u>lb mol</u>	<u>MW</u>	<u>kg</u>	<u>ELU/kg</u>	<u>ELU</u>
NO_x :	$(0.0024) (80.6)$	=	0.193	2.2	4.25	0.22	0.93
CO :	$(0.0018) (7.7)$	=	0.090	28	2.52	0.27	0.68
SO_2 :	$(0.014) (7.7)$	=	0.002	64	0.128	0.09	0.012
CO_2 :	$(0.986) (7.7)$	=	7.59	48	364	0.10	36.4

Total

38.0

the total lb mol of nitrogen (N) entering is $2(50) (0.806) + 0.001 = 80.6$

Solutions Chapter 11

11.1

2 (The two overall balances on A and B sum up to the overall balance on the system)

11.2

4 (such as 2 component balances for each unit)

11.3

	<u>Components</u>
Unit I involves A, B, C	3
Unit II involves D, E	2
Unit III involves A, B, C, D	4

Number of independent balances 9

If A and B are always combined in the same ratio, then you have to reduce the independent balances by 1 for Unit I and 1 for Unit III, a total of 2.

11.4

Six independent equations if all compositions are known. The sum of the components (in moles) would equal the total flow, hence not all of the equations that could be written would be independent, only 2 per subsystem.

Total balances:

Condenser

$$F_2 = F_4 + F_5 \quad (F_3 \text{ does not mix, hence cancels out or can be omitted})$$

Column

Solutions Chapter 11

$$F_1 + F_5 + F_9 = F_2 + F_8$$

Reboiler

$$F_8 = F_9 + F_7 \quad (F_6 \text{ does not mix, hence cancels out or can be omitted})$$

Component balances:

In addition, (2) component balances could be written for each component for each subsystem cited above. Multiply F_i by the composition x_{ij} .

11.5

Unknowns: stream flows including F: 6
Mass fractions (7 plus 3 in F) 10 16

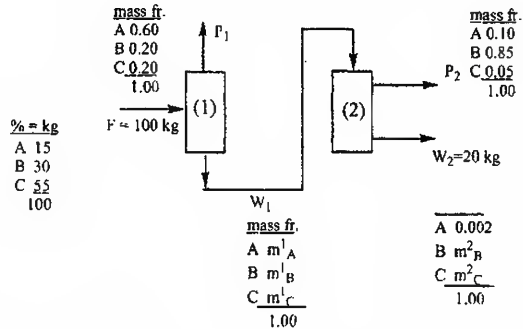
Independent material balances:

Species in i : 3
2 : 2
3 : 3 8

Other independent equations:

$$\sum \omega_i = 1 \text{ in each stream including F } \underline{8} \quad 16$$

11.6

Basis: $F = 100 \text{ kg}$ $m = \text{mass fraction}$ (a) SEPARATE ANALYSISColumn (1) balances

$$\begin{aligned}
 (1) \text{ A: } 0.15(100) &= W_1(m_A^1) + P_1(0.60) \\
 (2) \text{ B: } 0.30(100) &= W_1(m_B^1) + P_1(0.20) \\
 (3) \text{ C: } 0.55(100) &= W_1(m_C^1) + P_1(0.20) \\
 100 &= W_1 + P_1 \\
 (4) \quad m_A^1 + m_B^1 + m_C^1 &= 1
 \end{aligned}$$

any 3 are indept. eqns. } 4 indept. eqns.

Unknowns: $W_1, P_1, m_A^1, m_B^1, m_C^1$ 5 unknowns
 $5 - 4 = 1 \text{ degree of freedom}$

Column (2) balances

$$\begin{aligned}
 (5) \text{ A: } m_A^1 W_1 &= 0.10 P_2 + 0.002(20) \\
 (6) \text{ B: } m_B^1 W_1 &= 0.85 P_2 + m_B^2(20) \\
 (7) \text{ C: } m_C^1 W_1 &= 0.05 P_2 + m_C^2(20)
 \end{aligned}$$

any 3 are indept. eqns. } 5 indept. eqns.

$$W_1 = P_2 + 20$$

$$m_A^1 + m_B^1 + m_C^1 = 1$$

$$0.002 + m_B^2 + m_C^2 = 1$$

Unknowns: $W_1, P_2, m_A^1, m_B^1, m_C^1, m_B^2, m_C^2$ > unknowns
 $7 - 5 = 2 \text{ degrees of freedom}$

JOINT ANALYSIS

Adding the 2 units to make a joint system

	No. of <u>Unknowns</u>	No. of <u>indept. Eqns.</u>	Degrees <u>of freedom</u>
• From the separate calculations start with:	12	9	3
• Delete the 4 common variables W_1, m_A^1, m_B^1, m_C^1 that are treated as unknowns in both subsystems leaving:	8	9	-1
• Delete the equation $m_A^1 + m_B^1 + m_C^1$ that will no longer be independent in the joint system (it appears in both subsystems) once leaving:	8	8	0

(continued)

ANALYSIS OF OVERALL SYSTEM**System overall balances**

$$\left. \begin{aligned} (1) \text{ A: } 100(0.15) &= P_1(0.60) + P_2(0.10) + 20(0.002) \\ (2) \text{ B: } 100(0.30) &= P_1(0.20) + P_2(0.85) + 20(m_B^2) \\ (3) \text{ C: } 100(0.55) &= P_1(0.20) + P_2(0.05) + 20(m_C^2) \end{aligned} \right\} \begin{array}{l} 4 \text{ indept.} \\ \text{eqns.} \end{array}$$

$$0.002 + m_B^2 + m_C^2 = 1$$

Unknowns: P_1, P_2, m_B^2, m_C^2 4 unknowns
 $4 - 4 = 0$ degrees of freedom as expected

11.7**POLYMERIZATION****REQ SOLUTION**

$$\begin{aligned} P_1 &= 25.071618 \\ P_2 &= 9.5013366 \\ m_B^2 &= 10.786358 \\ m_C^2 &= 19.442702 \end{aligned}$$

REQ REPORT**Coefficient matrix and beta matrix**

	β	γ	δ	ϵ
0.01	0.18	0.25	0.28	10.9
0.08	0.28	0.2	0.58	12.5
0.54	0.42	0.04	0.2	20
0.15	0.14	0.01	0.02	14

The equations

$$\begin{aligned} (1) \text{ } 0.01x_1 + 0.08x_2 + 0.54x_3 + 0.15x_4 &= 10.9 \\ (2) \text{ } 0.08x_1 + 0.24x_2 + 0.10x_3 + 0.05x_4 &= 12.5 \\ (3) \text{ } 0.54x_1 + 0.42x_2 + 0.04x_3 + 0.02x_4 &= 20 \\ (4) \text{ } 0.01x_1 + 0.08x_2 + 0.15x_3 + 0.02x_4 &= 14 \end{aligned}$$

REQ SOLUTION

$$\begin{aligned} P_1 &= 25.183069 \\ P_2 &= 1.8973859 \\ m_B^2 &= 22.759138 \\ m_C^2 &= 22.30172 \end{aligned}$$

REQ REPORT**Coefficient matrix and beta matrix**

	β	γ	δ	ϵ
0.01	0.18	0.11	0.24	10.9
0.08	0.28	0.2	0.59	12.5
0.54	0.42	0.14	0.2	20
0.15	0.14	0.01	0.02	14

The equations

$$\begin{aligned} (1) \text{ } 0.01x_1 + 0.08x_2 + 0.54x_3 + 0.15x_4 &= 10.9 \\ (2) \text{ } 0.08x_1 + 0.24x_2 + 0.10x_3 + 0.05x_4 &= 12.5 \\ (3) \text{ } 0.54x_1 + 0.42x_2 + 0.14x_3 + 0.02x_4 &= 20 \\ (4) \text{ } 0.01x_1 + 0.08x_2 + 0.15x_3 + 0.02x_4 &= 14 \end{aligned}$$

REQ SOLUTION

$$\begin{aligned} P_1 &= 25.745214 \\ P_2 &= 20.220348 \\ m_B^2 &= 0.2223368 \\ m_C^2 &= 19.555497 \end{aligned}$$

REQ REPORT**Coefficient matrix and beta matrix**

	β	γ	δ	ϵ
0.01	0.18	0.11	0.24	10.9
0.08	0.28	0.2	0.59	12.5
0.54	0.42	0.14	0.2	20
0.15	0.14	0.01	0.02	14

The equations

$$\begin{aligned} (1) \text{ } 0.01x_1 + 0.08x_2 + 0.54x_3 + 0.15x_4 &= 10.9 \\ (2) \text{ } 0.08x_1 + 0.24x_2 + 0.10x_3 + 0.05x_4 &= 12.5 \\ (3) \text{ } 0.54x_1 + 0.42x_2 + 0.14x_3 + 0.02x_4 &= 20 \\ (4) \text{ } 0.01x_1 + 0.08x_2 + 0.15x_3 + 0.02x_4 &= 14 \end{aligned}$$

REQ SOLUTION

$$\begin{aligned} P_1 &= 24.098163 \\ P_2 &= 18.47108 \\ m_B^2 &= 11.847223 \\ m_C^2 &= 17.422301 \end{aligned}$$

REQ REPORT**Coefficient matrix and beta matrix**

	β	γ	δ	ϵ
0.01	0.18	0.19	0.24	10.9
0.08	0.28	0.2	0.59	12.5
0.54	0.42	0.14	0.2	20
0.15	0.14	0.01	0.02	14

The equations

$$\begin{aligned} (1) \text{ } 0.01x_1 + 0.08x_2 + 0.54x_3 + 0.15x_4 &= 10.9 \\ (2) \text{ } 0.08x_1 + 0.24x_2 + 0.10x_3 + 0.05x_4 &= 12.5 \\ (3) \text{ } 0.54x_1 + 0.42x_2 + 0.14x_3 + 0.02x_4 &= 20 \\ (4) \text{ } 0.01x_1 + 0.08x_2 + 0.15x_3 + 0.02x_4 &= 14 \end{aligned}$$

REQ SOLUTION

$$\begin{aligned} P_1 &= 24.129021 \\ P_2 &= 18.613062 \\ m_B^2 &= 11.870084 \\ m_C^2 &= 20.280864 \end{aligned}$$

REQ REPORT**Coefficient matrix and beta matrix**

	β	γ	δ	ϵ
0.01	0.18	0.19	0.24	10.9
0.08	0.28	0.2	0.59	12.5
0.54	0.42	0.14	0.2	20
0.15	0.14	0.01	0.02	14

The equations

$$\begin{aligned} (1) \text{ } 0.01x_1 + 0.08x_2 + 0.54x_3 + 0.15x_4 &= 10.9 \\ (2) \text{ } 0.08x_1 + 0.24x_2 + 0.10x_3 + 0.05x_4 &= 12.5 \\ (3) \text{ } 0.54x_1 + 0.42x_2 + 0.14x_3 + 0.02x_4 &= 20 \\ (4) \text{ } 0.01x_1 + 0.08x_2 + 0.15x_3 + 0.02x_4 &= 14 \end{aligned}$$

The results show that the system of equations is very sensitive to small perturbations in the coefficients (measurements).

Solutions Chapter 11

11.8

Basis: 1 hr (1000 kg)

a. Overall balances:

$$\text{Total: } 1000 = W + D$$

$$\text{Salt: } 1000(0.0345) = 0 + 0.069D$$

$$W = 500 \text{ kg}$$

$$D = 500 \text{ kg}$$

b. Salt balance on the freezer:

$$1000(0.0345) = 0 + 0.048B$$

$$B = 718.75 \text{ kg}$$

Total balance on the freezer:

$$1000 = A + B$$

$$A = 281.25 \text{ kg}$$

Total balance around filter:

$$B = 718.75 = C + D$$

$$C = 218.75 \text{ kg}$$

11.9

Basis: 220g 1gG from the reactor

$$\text{Fraction recovered} = \frac{140}{220} = 0.64$$

Solutions Chapter 11

11.10

Steps: 1, 2, 3, and 4: This is a steady state process with no reaction taking place. All the compositions are known except for stream C. We can pick the overall system first to get D, and then make balances on the first (or second) units to get C and its composition.

Step 5: Basis: $F = 290 \text{ kg}$ (equivalent to 1 second)

Step 6: Unknowns: A, B, C, D and E and the composition of C

Step 7: Balances: NaCl, HCl, H_2SO_4 , H_2O , inert solid

Step 8: For the overall system there are 4 unknowns (C is excluded) and 5 species balances:

Overall balances (kg)

	In		Out
NaCl:	$A(0.040)$	=	$290(0.0138)$
HCl:	$A(0.050)$	=	$290(0.0255) + D(0.020) + E(0.015)$
H_2SO_4 :	$A(0.040)$	=	$290(0.0221) + D(0.020) + E(0.015)$
H_2O :	$A(0.870) + B(0.910)$	=	$290(0.9232) + D(0.960) + E(0.970)$
Inerts:	$B(0.09)$	=	$290(0.0155)$
Totals:	$A + B$	=	$D + E + 290$

Steps 6 and 7:

Two of the equations are not independent: HCl and H_2SO_4 .

$$\text{HCl: } D(0.020) + E(0.015) = 7.40 - 5.00 = 2.40$$

$$\text{H}_2\text{SO}_4: D(0.020) + E(0.015) = 6.41 - 4.00 = 2.41$$

Thus, overall the degrees of freedom are 0.

Steps 8 and 9:

The solution of the equations is (in kg/s)

(continued)

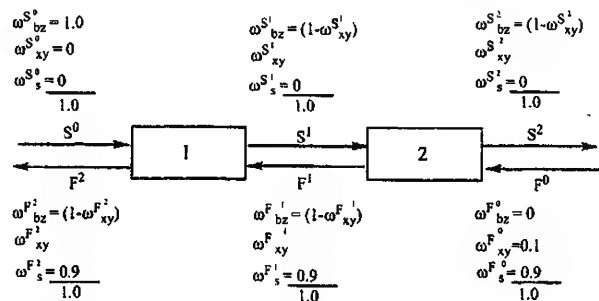
Solutions Chapter 11

$$A = 100, B = 50, D = 60 \text{ and } E = 80$$

from which $C = 150$ via a total balance about the first unit.

11.11

Notation: Subscripts Benzene = bz, Xylene = xy, Solids = s
W = mass fraction, F^i = liquid stream, S^i = solids stream



Step 5: Basis is 1 hr ($F^0 = 2000$ kg and $S^0 = 1000$ kg)

Steps 6 and 7:

Unknowns: $\left. \begin{array}{l} \text{Unit 1: } \omega_{xy}^F, \omega_{xy}^S, \omega_{xy}^F, S^1, F^1, F^2 \\ \text{Unit 2: } \omega_{xy}^F, \omega_{xy}^S, \omega_{xy}^F, S^1, F^1, S^2 \end{array} \right\} \text{Net} = 8$

Material Balances: Unit 1: bz, xy, s
Unit 2: bz, xy, s

Solutions Chapter 11

Additional Equations: $\omega_{xy}^F = \omega_{xy}^S$ and $\omega_{xy}^F = \omega_{xy}^S$ (the related equations for benzene are redundant). Total equations = 8.

The solution is simplified if two balances are made first (not an essential step):

All material balances are in kg.

Solids balance on Unit 2 and also Unit 1:

$$\begin{aligned} 2000(0.9) &= F^1(0.9) & F^1 &= 2000 \\ 2000(0.9) &= F^2(0.9) & F^2 &= 2000 \end{aligned}$$

Total balance on Unit 1 and also Unit 2:

$$\begin{aligned} 2000 + S^1 &= 2000 + S^2 & S^1 &= S^2 \\ 1000 + 2000 &= 2000 + S^1 & S^1 &= 1000 \\ & & S^2 &= 1000 \end{aligned}$$

The other balances are

Unit 2:

$$\begin{aligned} \text{Benzene: } 1000(1 - \omega_{xy}^S) &= 2000(1 - \omega_{xy}^F) + 1000(1 - \omega_{xy}^S) \\ \text{Xylene: } 2000(0.1) + 1000\omega_{xy}^S &= 2000\omega_{xy}^F + 1000\omega_{xy}^S \\ 10\omega_{xy}^F &= \omega_{xy}^S \end{aligned}$$

Unit 1:

$$\begin{aligned} \text{Benzene: } 1.0(1000) + 2000(1 - \omega_{xy}^F) &= 2000(1 - \omega_{xy}^F) + 1000(1 - \omega_{xy}^F) \\ \text{Xylene: } 0 + 2000\omega_{xy}^F &= 2000\omega_{xy}^F + 1000(\omega_{xy}^F) \\ 10\omega_{xy}^F &= \omega_{xy}^S \end{aligned}$$

Solve the equations to get the compositions of the streams:

(continued)

Solutions Chapter 11

Stream	Component wt fr	Stream	Component wt fr
S ⁰	Bz 1.0 Xy 0.0	F ⁰	Bz 0.9 Xy 0.1
S ¹	Bz 0.97 Xy 0.03	F ¹	Bz 0.082 Xy 0.018
S ²	Bz 0.82 Xy 0.18	F ²	Bz 0.097 Xy 0.003

b) Xylene in Feed = $2000 \times 0.1 = 200$ kg

Xylene in Product = $1000 \times 0.18 = 180$ kg

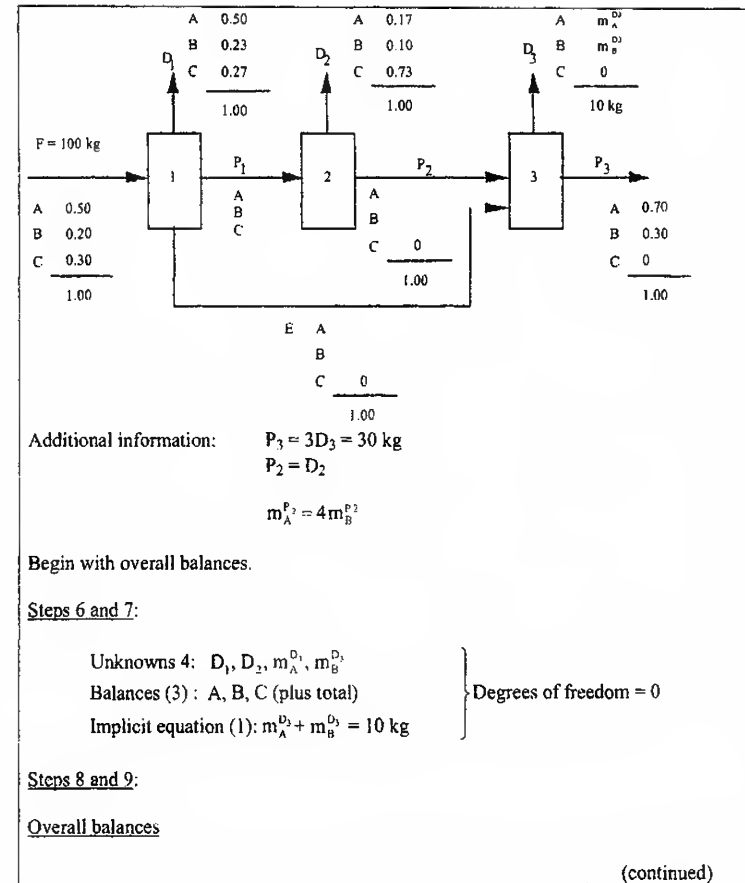
$$\% \text{ Recovery} = \frac{180}{200} \times 100 = 90\%$$

11.12

Step 5: Basis: F = 100 kg and D₃ = 10 kg

Steps 2, 3, and 4:

Solutions Chapter 11



Solutions Chapter 11

$$\text{Total: } 100 = D_1 + D_2 + 10 + 30 \quad \text{or } 60 = D_1 + D_2$$

$$C: 100(.30) = 0.27D_1 + 0.73D_2 + 0$$

Solve these two equations to get $D_1 = 30$ and $D_2 = 30$

Get $m_A^{D_1}$ and $m_B^{D_1}$ from A balance and $m_A^{D_1} + m_B^{D_1} = 1$

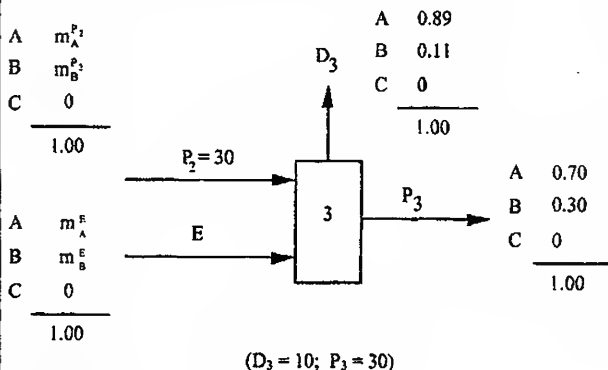
$$A: 100(.50) = 30(.50) + 30(.17) + 10m_A^{D_1} + 30(.70) \text{ so, } m_A^{D_1} = 0.89$$

$$m_A^{D_1} + m_B^{D_1} = 1 \text{ so } m_B^{D_1} = 0.11$$

Step 10:

Note - Can check using the B balance (not independent)

Balances on Unit No. 3



Steps 6 and 7:

Solutions Chapter 11

Unknowns (5): $E, m_A^B, m_B^B, m_A^E, m_B^E$

Balances (2): A, B

Implicit equations (2): $m_A^B + m_B^B = 30, m_A^E + m_B^E = E$

Other equations: $m_A^B = 4m_B^B$

Steps 8 and 9:

$$\text{Total: } 30 + E = D_3 + P_3 = 10 + 30 = 40 \quad \text{so} \quad E = 10 \text{ kg}$$

One component balance:

$$\left. \begin{array}{l} A: 30m_A^{P_2} + 10m_A^E = 10(.89) + 30(.70) = 29.9 \\ B: 30m_B^{P_2} + 10m_B^E = 10(.11) + 30(.30) = 10.1 \end{array} \right\} \text{not independent equations}$$

$$\left. \begin{array}{l} \Sigma m_i^{P_2} = m_A^{P_2} + m_B^{P_2} = 1 \\ m_A^{P_2} = 4m_B^{P_2} \end{array} \right\} \quad \begin{array}{l} m_B^{P_2} = 0.80 \\ m_A^{P_2} = 0.20 \end{array} \quad \text{so that}$$

$$30(.80) + 10m_A^E = 29.9 \text{ so that } m_A^E = 0.59 \quad \boxed{\text{or } 59\%}$$

$$\begin{array}{ll} m_A^E + m_B^E = 1 & m_B^E = 0.41 \quad \boxed{\text{or } 41\%} \\ \hline & 1.00 \end{array}$$

11.13

Two subsystems exist, hence 4 component balances can be written. No reaction occurs and the process is assumed to be in the steady state. Steps are omitted here. The balances are

System : Splitter

$$\begin{array}{l} \text{Total: } R = E + P \\ \text{Fiber: } 2.34 = x^E + x^P \\ \text{Water: } 7452 = 4161 + 3291 \end{array} \quad (a)$$

System : Stock Chest

$$\begin{array}{l} \text{Total: } P + N = L \\ \text{Fiber: } x^P + x^N = 103.26 \\ \text{Water: } 3291 + 18 = 3309 \text{ (continued)} \end{array}$$

Solutions Chapter 11

$$\text{Also } N(0.15) = 18 \quad N = 120$$

$$0.85(N) = x^N = 0.85(120) \quad (b)$$

Overall balances

$$\text{Total: } R + N = E + L$$

$$\text{Fiber: } 2.34 + x^N = x^E + 103.26 \quad (c)$$

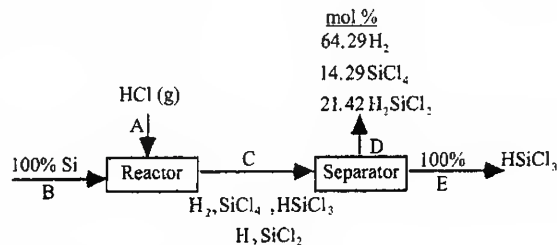
$$\text{Water: } 7452 + 18 = 4161 + 3309$$

Substitute (b) into (c), solve (c) for x^E , and then solve (a) for x^P .

$$\boxed{x^N = 102 \quad x^P = 1.26 \quad x^E = 1.08 \quad \text{all in kg}}$$

11.14

Steps 1, 2, 3 and 4:



Step 5: Basis: 100 kg B

$$\frac{100 \text{ kg Si}}{28.09 \text{ kg Si}} \left| \frac{1 \text{ kg mol Si}}{28.09 \text{ kg Si}} \right| = 3.560 \text{ kg mol Si}$$

Steps 6 and 7: Unknowns: A, D, E

Balances: H, Cl, Si

Solutions Chapter 11

Steps 8 and 9: Balances to be solved:

System: overall process

Si overall mole balance

$$\text{kg mol Si} = 3.560$$

$$= D \text{ kg mol gas} \left[\frac{0.1429 \text{ kg mol SiCl}_4}{\text{kg mol gas}} \left| \frac{1 \text{ kg mol Si}}{\text{kg mol SiCl}_4} \right| + \frac{0.2142 \text{ kg mol H}_2\text{SiCl}_2}{\text{kg mol gas}} \left| \frac{1 \text{ kg mol Si}}{\text{kg mol H}_2\text{SiCl}_2} \right| \right] + \frac{E \text{ kg mol HSiCl}_3}{\text{kg mol HSiCl}_3} \left| \frac{1 \text{ kg mol Si}}{\text{kg mol HSiCl}_3} \right| = 0.3571 D + E$$

Cl overall mol balance

$$\frac{A \text{ kg mol HCl}}{\text{kg mol HCl}} \left| \frac{1 \text{ kg mol Cl}}{\text{kg mol HCl}} \right| = D \text{ kg mol gas} \left[\frac{0.1429 \text{ kg mol SiCl}_4}{\text{kg mol gas}} \left| \frac{4 \text{ kg mol Cl}}{\text{kg mol SiCl}_4} \right| + \frac{0.2142 \text{ kg mol H}_2\text{SiCl}_2}{\text{kg mol gas}} \left| \frac{2 \text{ kg mol Cl}}{\text{kg mol H}_2\text{SiCl}_2} \right| \right] + \frac{E \text{ kg mol HSiCl}_3}{\text{kg mol HSiCl}_3} \left| \frac{3 \text{ kg mol Cl}}{\text{kg mol HSiCl}_3} \right|$$

$$A = D + 3E$$

H overall mol balance

(continued)

$$\frac{A \text{ kg mol HCl}}{1 \text{ kg mol HCl}} = D \text{ kg mol gas} \left[\frac{0.6429 \text{ kg mol H}_2}{\text{kg mol gas}} \right] \frac{2 \text{ kg mol H}}{\text{kg mol H}_2}$$

$$+ \frac{0.2142 \text{ kg mol H}_2\text{SiCl}_2}{\text{kg mol gas}} \left[\frac{2 \text{ kg mol H}}{\text{kg mol H}_2\text{SiCl}_2} \right] + \frac{E \text{ kg mol HSiCl}_2}{1 \text{ kg mol HSiCl}_2}$$

$$A = 1.7142D + E$$

Solution: $3.560 = 0.3571 D + E$ ①

$$A = D + 3E$$
 ②

$$A = 1.7142D + E$$
 ③

② ③ $2E = 0.7142 D$

$$E = 0.3571 D$$
 ④

① ④ $\rightarrow 3.56 = 0.3571 D + 0.3571 D$

$$D = 4.98$$

$$E = 1.78$$

$$A = 10.32$$

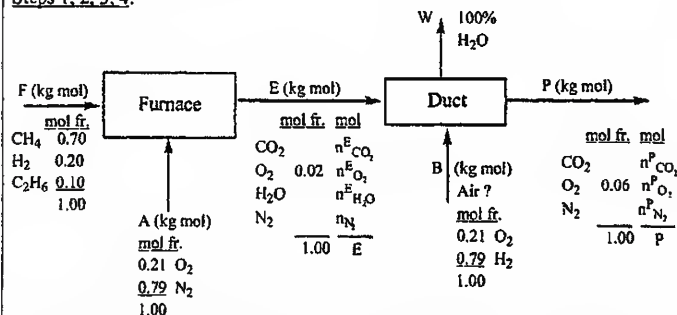
	MW
H	1.01
Si	28.09
Cl ₃	106.35
	135.45 kg/mol

$$\frac{135.45 \text{ kg HSiCl}_2}{\text{kg mol HSiCl}_2} \left[\frac{1.78 \text{ kg mol}}{\text{kg mol HSiCl}_2} \right] = 241 \text{ kg HSiCl}_2$$

11.15

Step 5: Basis: 100 kg mol = F

Steps 1, 2, 3, 4:



Assume first an air leak occurs and use material balances to calculate the amount. This is a steady state flow process without reaction.

Overall system

Step 6: Unknowns are: A, B, W, P, x_{N_2} (or n_{N_2}), x_{CO_2} (or n_{CO_2})

Step 7: Balances are: C, H, O, N, $\sum x_i^P = 1$ (or $\sum n_i^P = P$)

(continued)

Solutions Chapter 11

Step 8:

	In	Out
C (kg mol):	$0.70(100) + 0.10(100)2$ $n_{\text{CO}_2} = 90 \text{ kg mol}$	$= n_{\text{CO}_2}$
H (kg mol):	$0.70(100)(4) + 0.20(100)(2) + 0.10(100)(6) = W(2)$ $W = 190 \text{ kg mol}$	
2O (kg mol):	$0.21A + 0.21B$	$= \frac{190(1.00)}{2} + 90 + 0.06P$
2N (kg mol):	$0.79A + 0.79B$ $90 + 0.06P + n_{\text{N}_2}^{\text{P}}$	$= n_{\text{N}_2}^{\text{P}}$ $= P$

A balance about the furnace or about the duct is needed, or those two alone would have been sufficient, omitting the overall balance.

System: Duct

Step 6: Unknowns: A, E, $n_{\text{CO}_2}^{\text{E}}$, $n_{\text{O}_2}^{\text{E}}$, $n_{\text{H}_2\text{O}}^{\text{E}}$

Step 7: Balances: C, H, O, N_2 , $\sum n_i^{\text{E}} = E$

Steps 8 and 9:

C (kg mol):	$0.70(100) + 0.10(100)(2) = n_{\text{CO}_2}^{\text{E}}$ $n_{\text{CO}_2}^{\text{E}} = 90 \text{ kg mol}$
H (kg mol):	$0.70(100)(4) + 0.20(100)(2) + 0.10(100)(6) = n_{\text{H}_2\text{O}}^{\text{E}}$ $n_{\text{H}_2\text{O}}^{\text{E}} = 190$
2O (kg mol):	$0.21A = n_{\text{O}_2}^{\text{E}} + 90 + \frac{190}{2}$
2N (kg mol):	$0.79A = n_{\text{N}_2}^{\text{E}}$ $90 + 190 + n_{\text{O}_2}^{\text{E}} + n_{\text{N}_2}^{\text{E}} = E$
	$0.02 = \frac{n_{\text{O}_2}^{\text{E}}}{E}$

Solutions Chapter 11

Solution

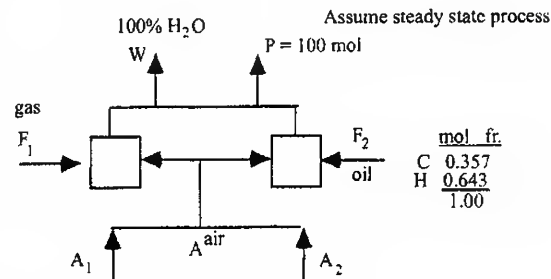
	kg mol in E		kg mol
$n_{\text{CO}_2}^{\text{E}}$	90	A	982
$n_{\text{H}_2\text{O}}^{\text{E}}$	190	E	1077
$n_{\text{O}_2}^{\text{E}}$	21.5		
$n_{\text{N}_2}^{\text{E}}$	<u>776</u>		
	1077.5		

From the overall 2N balance $0.79(982) + 0.79B = n_{\text{N}_2}^{\text{P}}$ (1)

2O balance $0.21(982) + 0.21B = 185 + 0.06P$ (2)

(1') $22.2 + 0.21B = 0.06P$
 (3) $90 + (0.79)(982) + 0.79B = 0.94P$ } $B = 207 \text{ kg mol}$
 $P = 1095 \text{ kg mol}$ 207 kg mol / 100 kg mol F

11.16



Basis: 100 mol natural gas

(continued)

Solutions Chapter 11

<u>Comp.</u>	<u>mol=%atoms C</u>	<u>atoms O</u>	<u>atoms H</u>	
CH ₄	96	96	--	384
C ₂ H ₂	2	4	--	4
CO ₂	2	2	4	--
Total	<u>100</u>	<u>102</u>	<u>4</u>	<u>388</u>

Basis: 100 mol oil

<u>Comp.</u>	<u>atoms C</u>	<u>atoms H</u>
(CH _{1.8}) _n	100	180

Basis: 100 mol flue gas (dry)

<u>Comp.</u>	<u>mol%</u>	<u>mol C</u>	<u>mol O</u>	<u>atoms H</u>	<u>mol N₂</u>
CO ₂	10.0	10.00	20.00	--	
CO	0.63	0.63	0.63	--	
O ₂	4.55	--	9.10	--	
N ₂	<u>84.82</u>	<u>--</u>	<u>--</u>	<u>--</u>	<u>84.82</u>
Total	100.00	10.63	29.73	--	84.82

Note: If have separate air streams, we have 5 unknowns and can't solve.

Basis: 100 mol natural gas (or use 100 mol dry gas product.)

Let F₂ = mol oilF₁ or P = mol dry flue gas

A = mol air to natural gas fed boiler plus oil fed boiler

W = mol water associated with the dry flue gas

Solutions Chapter 11

Four balances: In = Out

C balance

$$102 + F_2 = 0.1063 P \quad (1)$$

N₂ balance

$$0.79A = 0.8482 P \quad (2)$$

H balance

$$388 + 1.80 F_2 = 2 W \quad (3)$$

O balance

$$4 + 0.42A = 0.2973P + W \quad (4)$$

$$P = 1729 \text{ mol dry flue gas}$$

$$W = 268 \text{ mol H}_2\text{O}$$

$$F_2 = 82 \text{ mol oil and 1 mol C = 1 mol oil so}$$

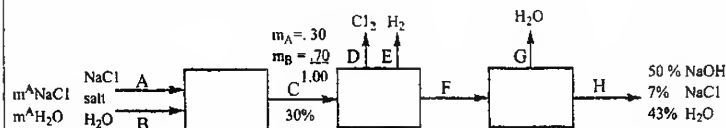
$$\text{C in oil} = F_2 = 82 \text{ mol}$$

$$\text{Total C} = 102 + 82 = 184 \text{ mol}$$

$$\% \text{ C burned from oil} = \frac{(0.82)(100)}{184} = \boxed{44.5\%}$$

11.17

Steady-state, reaction take place

Overall balancesSteps 6 and 7:

5 unknowns: A, B, D, E, G

4 balances: Na, Cl, H, O

other equations: $A/B = 30/70$ Steps 8 and 9:

(a) Percent conversion of salt to sodium hydroxide.

Basis: 1 lb product = H

1 lb mol of NaOH:

$$\frac{1 \text{ lb}}{1} \left| \frac{0.5 \text{ lb NaOH}}{40 \text{ lb NaOH}} \right| \frac{\text{lb mol NaOH}}{\text{lb}} = 1.25 \times 10^{-2} \text{ lb mol NaOH}$$

1 lb mol NaCl:

$$\frac{1 \text{ lb}}{1} \left| \frac{0.07 \text{ lb NaCl}}{58.45 \text{ lb NaCl}} \right| \frac{\text{lb mol NaCl}}{\text{lb}} = 1.20 \times 10^{-3} \text{ lb mol NaCl}$$

$$\text{Conversion} = \frac{1.25 \times 10^{-2}}{1.25 \times 10^{-2} + 1.20 \times 10^{-3}} (100) = \boxed{91.2\%}$$

(b) How much chlorine gas is produced per lb of product?

$$\frac{1.25 \times 10^{-2} \text{ lb mol NaOH}}{1 \text{ lb mol NaOH}} \left| \frac{0.5 \text{ lb mol Cl}_2}{70.9 \text{ lb Cl}_2} \right| \frac{\text{lb mol Cl}_2}{\text{lb mol NaOH}} = \boxed{0.44 \text{ lb Cl}_2/\text{lb product}}$$

$$(c) \quad A = (1.25 \times 10^{-2} \text{ lb mol} + 1.20 \times 10^{-3} \text{ lb mol}) \left(\frac{58.45 \text{ lb}}{\text{lb mol}} \right) = 0.80 \text{ lb}$$

Using salt as a tie component:

$$C = \frac{A}{0.30} = \frac{1}{0.30} \cdot 0.8 \text{ lb} = 2.67 \text{ lb}$$

$$B = C - A = 2.67 - 0.8 = 1.87 \text{ lb}$$

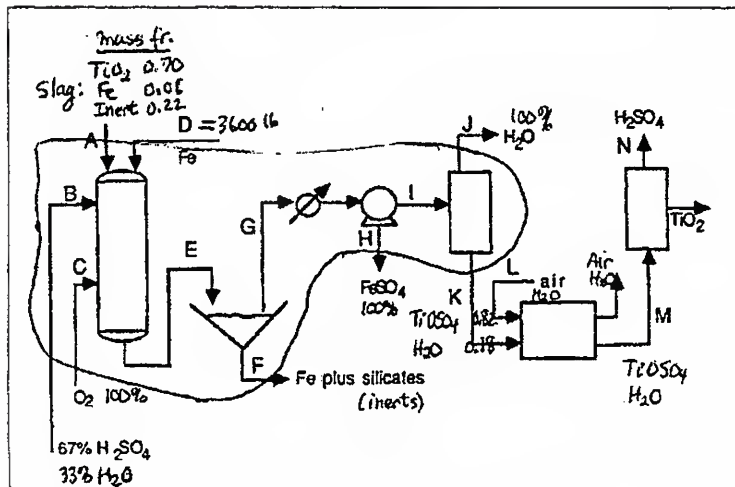
Balance on oxygen:

$$G = \left(\frac{1.87 \text{ lb}}{18 \text{ lb}} \frac{\text{mol}}{\text{lb}} - \frac{0.43 \text{ lb}}{18 \text{ lb}} \frac{\text{mol}}{\text{lb}} - \frac{0.50 \text{ lb}}{40 \text{ lb}} \frac{\text{mol}}{\text{lb}} \right) \left(\frac{18 \text{ lb}}{\text{mol}} \right) = \boxed{1.22 \text{ lb}}$$

11.18

Step 5: Basis = 100 lb ASteps 2, 3, and 4:Fe added: $36(100) = 3600 \text{ lb}$ MW $\text{TiO}_2 = 79.9 \text{ lb/lb mol}$ MW Fe = 55.8 lb/lb mol MW $\text{H}_2\text{SO}_4 = 98.1 \text{ lb/lb mol}$ MW $\text{TiOSO}_4 = 159.7 \text{ lb/lb mol}$

(continued)



For Part (a), the system boundary has been drawn on a light solid line.

Steps 6 and 7:

Unknowns (9): B, C, J, K, H, F, ξ_1 , ξ_2 , m_{Fe}^F

Species balances (7): TiO_2 , Fe, H_2SO_4 , H_2O , TiOSO_4 , O_2 , inert

Other equations (2): Reactions 1 and 2 are complete

Degrees of freedom = 0

Steps 8 and 9

a. lb H_2O removed in evaporator (J):

Mol TiO_2 in slag:

Mol Fe in slag:

$$\frac{(0.70)(100 \text{ lb})}{79.9 \text{ lb}} = 0.876 \text{ lb mol}$$

$$\frac{(0.06)(100 \text{ lb})}{58.8 \text{ lb}} = 0.102 \text{ lb mol}$$

Amount of H_2SO_4 based on theoretical requirements of Equations (1) and (2)

$$0.876 + 0.102 = 1.02 \text{ lb mol } \text{H}_2\text{SO}_4$$

$$\frac{1.02 \text{ lb mol } \text{H}_2\text{SO}_4}{1 \text{ lb mol}} \times 98.1 \text{ lb} = 100 \text{ lb } \text{H}_2\text{SO}_4$$

$$B = \frac{100 \text{ lb}}{0.67} = 149.2 \text{ lb} \quad \text{Water in stream B} = 49.2 \text{ lb}$$

$$\text{O}_2 \text{ in: } \frac{0.143 \text{ lb mol Fe}}{1 \text{ lb mol Fe}} \times \frac{0.5 \text{ lb mol O}_2}{1 \text{ lb mol Fe}} \times \frac{32 \text{ lb O}_2}{1 \text{ lb mol O}_2} = 2.29 \text{ lb O}_2 = C \text{ (0.0715 lb mol)}$$

$$\text{Using } \text{TiO}_2: \quad \xi_1 = \frac{0 - 0.876}{(-1)} = 0.876 \text{ moles reacting}$$

$$\text{Using } \text{O}_2: \quad \xi_2 = \frac{0 - 0.0715}{(0.5)} = 0.143 \text{ moles reacting}$$

TiOSO_4 in stream K

$$n_{\text{TiOSO}_4}^K = 0 + (1)(0.876) = 0.876 \text{ lb mol } \text{TiOSO}_4$$

$$K = \frac{0.876 \text{ lb mol}}{1 \text{ lb mol}} \times \frac{159.7 \text{ lb}}{0.82} = 170.6 \text{ lb}$$

$$\text{H}_2\text{O in K} = 170.6 (0.18) = 30.7 \text{ lb}$$

Water formed in the reactions (use ξ_1 and ξ_2):

(continued)

$$n_{\text{H}_2\text{O}}^{\text{out, tot}} = (1)(0.876) + (1)(0.143) = 1.019 \text{ lb mol (or 8.36 lb H}_2\text{O)}$$

Water exiting from the evaporator J (lb):

$$49.2 + 18.36 - 30.7 = \boxed{36.9 \text{ lb}}$$

b. Exit H₂O from dryer:

$$\text{inlet air} = \frac{18 \text{ lb mol}}{\text{lb mol}} \bigg| \frac{29 \text{ lb}}{\text{lb mol}} = 522 \text{ lb dry air}$$

$$\text{inlet water} = \frac{0.036 \text{ mol H}_2\text{O}}{\text{mol air}} \bigg| \frac{18 \text{ mol air}}{\text{lb mol}} \bigg| \frac{18 \text{ lb}}{\text{lb mol}} = 11.7 \text{ lb H}_2\text{O}$$

$$\text{water added to air} = (0.18) 170.9 \text{ lb} - (0.876 \text{ lb mol}) \frac{18 \text{ lb}}{\text{lb mol}} = 15.0 \text{ lb}$$

$$\text{Humidity} = (15.0 \text{ lb H}_2\text{O} + 11.7 \text{ lb H}_2\text{O}) / 522 \text{ lb air}$$

$$= \boxed{0.051 \text{ lb H}_2\text{O/lb air}}$$

c. The pounds of TiO₂ produced (P):

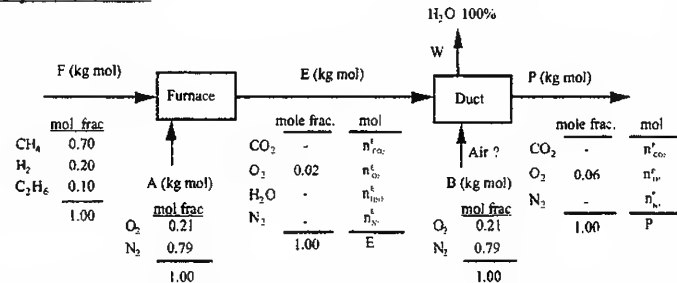
By reaction (3), 0.876 lb mol of TiOSO₄ goes to TiO₂.

$$(0.876) (79.9) = \boxed{70 \text{ lb}} \text{ TiO}_2$$

11.19

Step 5: Basis: 100 kg mol = F

Steps 1, 2, 3, and 4:



Assume an air leak occurs first and use material balances to calculate the amount. This is a steady state flow process without reaction.

Overall system

Step 6: Unknowns are: A, B, W, P, x_{N_2} (or n_{N_2}), x_{CO_2} (or n_{CO_2})

Step 7: Balances are: C, H, O, N, $\sum x_i = 1$ (or $\sum n_i = P$)

Steps 8 and 9:

	In		Out
C (kg mol):	$0.70(100) + 0.10(100) 2$	=	n_{CO_2}
	$n_{\text{CO}_2} = 90 \text{ kg mol}$		

(continued)

Solutions Chapter 11

$$\text{H (kg mol): } 0.70 (100)(4) + 0.20 (100)(2) + 0.10 (100)(6) = W (2)$$

$$W = 190 \text{ kg mol}$$

$$2\text{O (kg mol): } 0.21A + 0.21B = \frac{190(1.00)}{2} + 90 + 0.06P$$

$$2\text{N (kg mol): } 0.79A + 0.79B = n_{N_2}^P$$

$$90 + 0.06P + n_{N_2}^P = P$$

A balance about the furnace or about the duct is needed; or these two alone would have been sufficient, omitting the overall balance.

System: Furnace (or Duct)

Step 6: Unknowns: $A, n_{CO_2}^E, n_{O_2}^E, n_{H_2O}^E, n_{N_2}^E$

Step 7: Balances: $C, H, O, N_2, \sum n_i^E = E$

Steps 8 and 9:

$$\text{C (kg mol): } 0.70 (100) + 0.10 (100)(2) = n_{CO_2}^E$$

$$n_{CO_2}^E = 90 \text{ kg mol}$$

$$\text{H (kg mol): } 0.70 (100)(4) + 0.20 (100)(2) + 0.10 (100)(6) = n_{H_2O}^E$$

$$n_{H_2O}^E = 190$$

$$2\text{O (kg mol): } 0.21A = n_{O_2}^E + 90 + \frac{190}{2}$$

$$2\text{N (kg mol): } 0.79A = n_{N_2}^E$$

$$90 + 190 + n_{O_2}^E + n_{N_2}^E = E$$

Solutions Chapter 11

$$0.02 = n_{O_2}^E / E$$

<u>Solution:</u>	<u>kg mol in E</u>		<u>kg mol</u>
$n_{CO_2}^E$	90	A	982
$n_{H_2O}^E$	190	E	1077
$n_{O_2}^E$	21.5		
$n_{N_2}^E$	776		
	1077.5		

$$\text{From the overall } N_2 \text{ balance: } 0.79 (982) + 0.79B = n_{N_2}^P \quad (1)$$

$$O_2 \text{ balance: } 0.21 (982) + 0.21B = 185 + 0.06P \quad (2)$$

$$(1) \quad 22.2 + 0.21B = 0.06P \quad B = 207 \text{ kg mol}$$

$$(3) \quad 90 + (0.79)(982) + 0.79B = 0.94P \quad P = 1095 \text{ kg mol}$$

It is an air leak.

$$207 \text{ kg mol} / 100 \text{ kg mol F}$$

Solutions Chapter 11

11.20

Basis: Data given

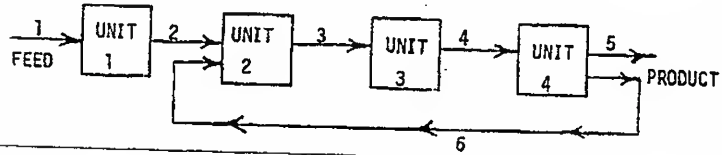
<u>Stage</u>	<u>Activity (units)</u>	<u>Protein present (mg)</u>	<u>Specific Activity (units/mg)</u>	<u>Recovery (%)</u>	<u>Purification</u>
After breakage of cell	6,860	76,200	0.09	100	-
After adsorption/ desorption step	6,800	2,200	3.1	99	34
After second adsorption/ desorption step	5,300	267	19.9	78	213

Solutions Chapter 12

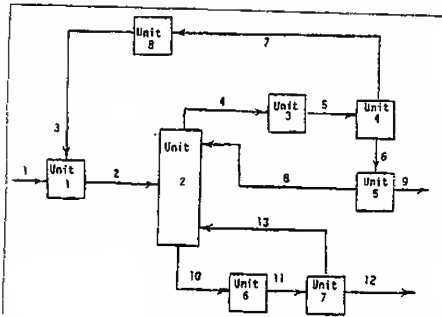
12.1

a. 1; b. 3; c. 0; d. 7

a.

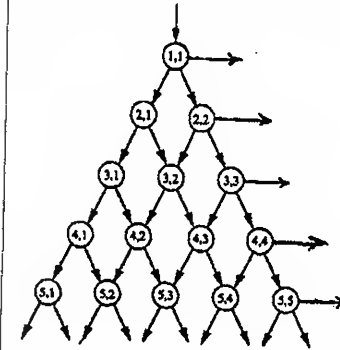


b.

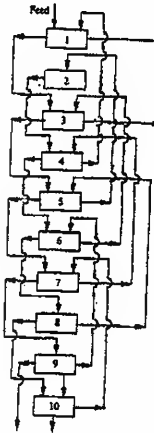


Solutions Chapter 12

c.



d.



Solutions Chapter 12

12.2

Step 5: Basis: 60 kg W

Pick the overall system

Steps 6 and 7:

Unknowns: F, P

Balances: A, B

Steps 8 and 9:

$$\left. \begin{array}{l} \text{Total } F = 60 + P \\ \text{B: } 0.80F = 0 + 0.95P \end{array} \right\} \begin{array}{l} F = 380 \text{ kg} \\ P = 320 \text{ kg} \end{array}$$

Pick mixing point as the system

Steps 6 and 7:

Unknowns: G, R

Balances: A, B (or total as alternate)

Steps 8 and 9:

$$\left. \begin{array}{l} \text{Total: } 380 + R = G \\ \text{B: } 0.80(380) + R(0) = 0.60G \end{array} \right\} R = 126.7$$

$$\frac{R}{F} = \frac{126.7}{380} = \boxed{0.33} \text{ kg R/kg F}$$

Solutions Chapter 12

12.3

Basis: 100 kg of fresh feed

Overall balance around junction

$$100 + R = F$$

KC1 balance around mixing point

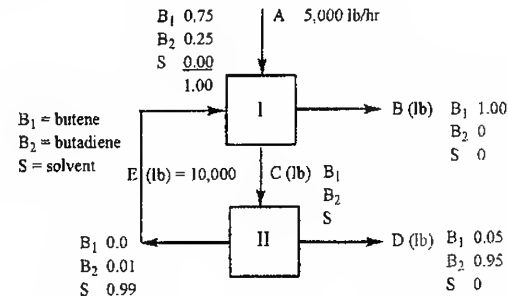
$$20 + 0.6 R = 0.4 F = 0.4 (100 + R)$$

$$20 + 0.6 R = 40 + 0.4 R$$

$$R = \boxed{100 \text{ kg R/100 kg fresh feed}}$$

12.4

Steps 2, 3, and 4:



(continued)

Solutions Chapter 12

Step 5: Basic: 1 hr ($A = 5000$ lb)

Select whole process as the system.

Steps 6 and 7:

Unknowns: B, D

Balances: Total, B_1 , B_2 , S (not all independent)

Steps 8 and 9:

Total balance: $5000 = B + D$

B_1 balance: $5000(0.75) = B(1) + D(0.05)$

$$D = 1316 \text{ lb} \quad B = 3684$$

Apparently the calculated values are not correct. (The value for C can be obtained from balances on Unit I or II).

12.5

Basis: 1 hour

An overall balance shows that R_{out} from the adsorber must equal R_{in} to the adsorber if a steady state exists. Let $R_i = R$.

Adsorber balance of U (units are U):

$$\frac{600 \text{ mL}}{1 \text{ mL}} \left| \frac{1.37U}{1 \text{ mL}} \right| + \frac{R \text{ mL}}{1 \text{ mL}} \left| \frac{5.2U}{1 \text{ mL}} \right| = \frac{600 \text{ mL}}{1 \text{ mL}} \left| \frac{0.08U}{1 \text{ mL}} \right| + \frac{R \text{ mL}}{1 \text{ mL}} \left| \frac{19.3U}{1 \text{ mL}} \right|$$

$$600(1.37 - 0.08) = R(19.3 - 5.2)$$

$$R = 55 \text{ mL/hr}$$

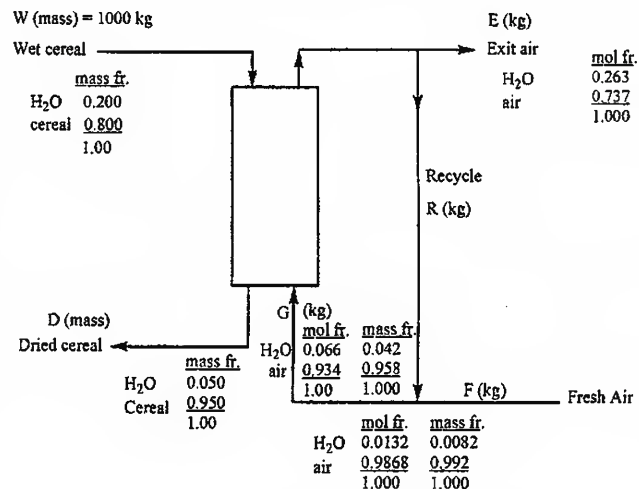
Solutions Chapter 12

12.6

Step 5: Basis: $1000 \text{ kg} = W \equiv 1 \text{ hour}$

Steps 1-4: Revised compositions are in mass fractions.

Note: compositions identical



Conversion of mole fractions to mass fractions is not required, but since both mass fractions and mol fractions are listed as data, convert all to mass fractions (can't convert cereal to mol) to avoid confusion in making the balances.

(continued)

Solutions Chapter 12

Fresh air, Basis 100 mol					Exit air, Basis 1.00 mol			
	mol	MW	mass(kg)	mass fr.	mol	MW	mass	mass fr.
air	98.68	29	2861.7	0.992	0.737	29	21.37	0.819
H ₂ O	<u>1.32</u>	18	<u>23.76</u>	<u>0.0082</u>	<u>0.263</u>	18	<u>4.73</u>	<u>0.181</u>
	100.00		2885.48	1.000	1.00		26.11	1.000

Air entering drier, basis 1.00 mol				
	mol	MW	mass	mass fr.
air	0.934	29	27.09	0.958
H ₂ O	0.066	18	1.19	0.042
			28.27	1.000

Overall balances (unknowns D, E, F; balances H₂O, cereal, air)

Total: can be made in mass: $1000 + F = E + D$

in

cereal (dry): $1000 (0.80) + F (0) = E (0) + D (0.950) \quad D = 842 \text{ kg}$

H₂O: $1000 (0.20) + F (0.0082) = E (0.181) + D (0.050)$

air: $1000 (0) + F (0.992) = E (0.819) + D (0)$

3 are independent eqns. check by 4th eqn.

a. $D = 842 \text{ kg}$ $F = 748 \text{ kg/hr}$

$E = 906 \text{ kg}$

Balance on mixing point (to get R)

Total: $R + F = G$

air: $R (0.819) + F (0.992) = G (0.958)$

H₂O: $R (0.181) + F (0.0082) = G (0.042)$

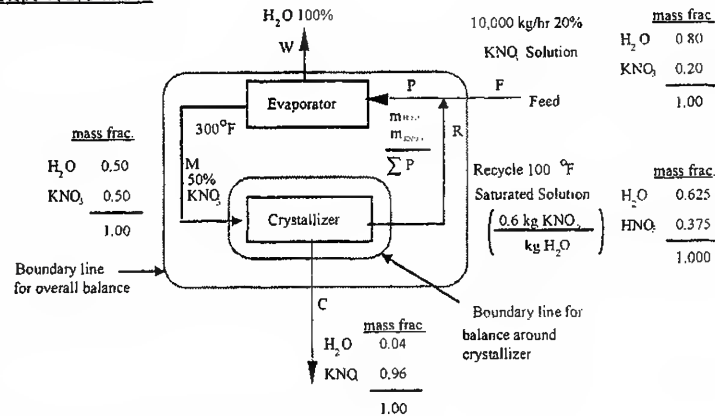
2 equations are independent, check via 3d equation

b. $R = 183 \text{ kg/hr}$

Solutions Chapter 12

12.7

Steps 1, 2, 3 and 4:



Step 5: Basis: 1 hr = 10,000 kg KNO₃ solution

Step 4 cont'd:

Compute the weight fraction composition of R. On the basis of 1 kg of water, the saturated recycle steam contains (1.0 kg of H₂O + 0.6 kg of KNO₃) = 1.6 kg total. The recycle steam composition is

$$\frac{0.6 \text{ kg KNO}_3}{1 \text{ kg H}_2\text{O}} \bigg| \frac{1 \text{ kg H}_2\text{O}}{1.6 \text{ kg solution}} = 0.375 \text{ kg KNO}_3 / \text{kg solution}$$

or 37.5% KNO₃ and 62.5% H₂O (which has been added to the figure). (continued)

Analysis of complete process (6 streams):

Unknowns: $W, M, C, R, m_{H_2O}^P, m_{KNO_3}^P$ = 6

Balances: (2 units + 1 mix point) $\times$ 2 components = 6

Other compositions are (in %)

	$\underline{M}$	$\underline{F}$	$\underline{W}$	$\underline{C}$	$\underline{R}$
H_2O	50	80	100	4	62.5
KNO_3	50	20	0	96	37.5

Start with overall balances as substitute for unit balances

Steps 6 and 7: Unknowns: $W, C,$

Balances: 2 components

Overall balance to calculate C: Total: 10,000 = $W + C$

$$KNO_3: 10,000 (0.20) = W (0) + C (0.96)$$

$$\frac{10,000 \text{ kg F}}{1 \text{ hr}} \left| \frac{0.20 \text{ kg } KNO_3}{1 \text{ kg F}} \right| \frac{1 \text{ kg crystals}}{0.96 \text{ kg } KNO_3} = 2083 \text{ kg / hr crystals} = C$$

$$W = 10,000 - 2083 = 7917 \text{ kg}$$

To determine the recycle stream R, we need to make a balance that involves the stream R. Either (a) a balance around the evaporator or (b) a balance around the crystallizer will do. The latter is easier since only three rather than four (unknown) streams are involved.

Total balances on crystallizer:

$$M = C + R$$

$$M = 2083 + R \quad \textcircled{a}$$

Component (KNO_3) balance on crystallizer:

$$M \omega_M = C \omega_C + R \omega_R$$

$$0.5M = 0.96C + R \quad (0.375) \quad \textcircled{b}$$

Solving equations $\textcircled{a}$ and $\textcircled{b}$ we obtain

$$0.5 (2083 + R) = 0.375R + 2000$$

$$\boxed{R = 7670 \text{ kg/hr}}$$

12.8

Step 5: Basis: 1000 lb/hr sea water

Steps 6 and 7:

Pick the whole process as the system

Unknowns: B, D

Balances: salt, water

Steps 8 and 9:

$$\text{Overall mass balance: } B + D = 1000 \quad (1)$$

$$\text{Overall salt balance: } 0.0525B + 5.0 \times 10^{-4} D = 31 \quad (2)$$

Pick the mixing point as the system

Unknowns: R, W

(continued)

Solutions Chapter 12

Balances: salt, water

Mass balance around the junction: $1000 + R = W$ (3)

where R = brine recycle; W = total soln entering the cell

Salt balance around the junction: $31 + 0.0525 R = 0.04W$ (4)

From (1) & (2): $B = 586 \text{ lb/hr}$ & $D = 414 \text{ lb/hr}$

From (3) & (4): $R = 720 \text{ lb/hr}$

$$\text{Fraction} = \frac{720}{720 + 586} = 0.551$$

12.9

Basis: 1 hr $\equiv 1 \text{ L} = F$ all concentrations are g/L.

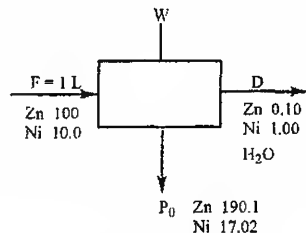


Figure P12.9

Pick the overall process as the system.

Solutions Chapter 12

Steps 6 and 7:

Balances: 3 $\text{H}_2\text{O}, \text{Zn}, \text{Ni}$

Unknowns: 3 W, D, P_0 (all in L)

Steps 8 and 9:

Zn: $100(1) + 0 = \frac{D(L)}{L} \left| \frac{0.10 \text{ g}}{L} \right. + P_0(190.1 \text{ g/L})$

Ni: $10(1) + 0 = D(1.00) + P_0(17.02)$ $F \cdot W = P_0 \cdot Q$

Solve to get $P_0 = 0.525 \text{ L}$ $D = 1.056 \text{ L}$ $W = 0.581 \text{ L}$

Pick Unit 3 as the system:

Steps 6 and 7:

Balances: 3 $\text{H}_2\text{O}, \text{Zn}, \text{Ni}$

Unknowns: 3 W, R_{32}, P_2 (all in L)

Steps 8 and 9:

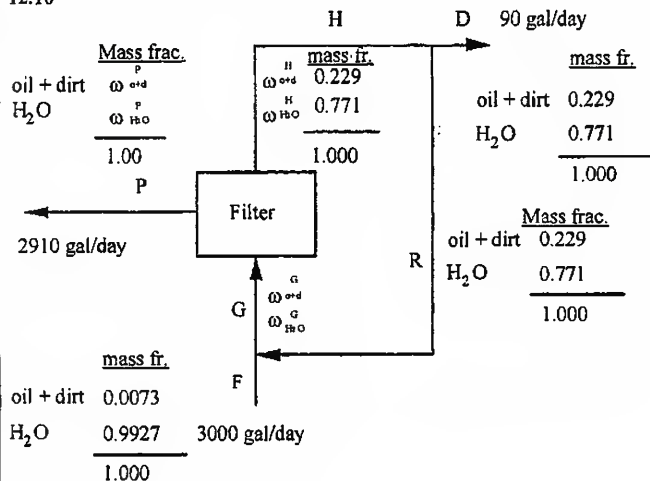
Zn: $P_2(3.50) + 0 = 0.10(1.056) + R_{32}(4.35)$

Ni: $P_2(2.19) + 0 = 1.00(1.056) + R_{32}(2.36)$

Solve to get $R_{32} = 2.75 \text{ L/hr}$

Solutions Chapter 12

12.10



Pick the total process as the system

Step 5: Basis: 1 day (equivalent to $D = 90$ gal, $F = 3000$ gal, $P = 2910$ gal)

Steps 6 and 7:

Unknowns: $\omega_{\text{oil+d}}^P$, $\omega_{\text{H}_2\text{O}}^P$

Balances: oil + dirt, H_2O

Steps 8 and 9:

Overall oil + dirt balance: $\text{In} = \text{Out}$
 $3,000(0.0073) = 2,910(\omega_{\text{oil+d}}^P) + 90(0.229)$

Solutions Chapter 12

$$\omega_{\text{oil+d}}^P = \frac{21.9 - 20.61}{2,910} = 4.43 \times 10^{-4} \quad (\text{a})$$

To solve for R , make balances on the mixing point, the filter, and the splitter. Not all of the balances are independent:

	<u>Total</u>	<u>oil + dirt</u>
<u>Splitter:</u>	$H = 90 + R$	$0.229H = 0.229(90) + 0.229(R)$
<u>Filter:</u>	$G = 2910 + H$	$\omega_{\text{oil+d}}^G G = 2910(4.43 \times 10^{-4}) + H(0.229)$
<u>Mixing point:</u>	$3000 + R = G$	$0.0073(3000) + 0.229R = \omega_{\text{oil+d}}^G G$

Unknowns: H , R , G , $\omega_{\text{oil+d}}^G$

Balances: 6 (4 independent)

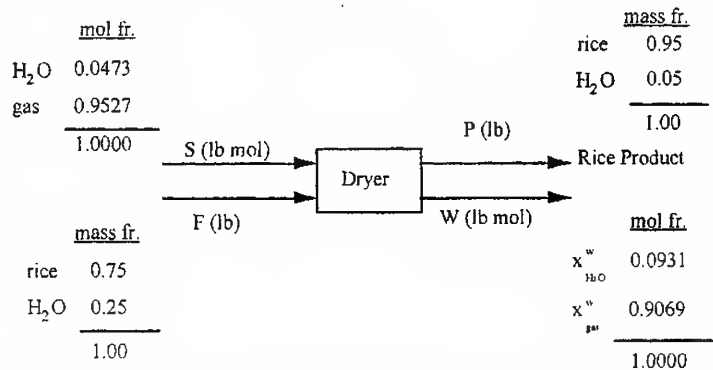
Steps 8 and 9:

The solution is $R = 57.2$ gal/day $\omega_{\text{oil+d}}^G = 0.01145$

Solutions Chapter 12

12.11

Start with the overall system



Steps 1, 2, 3 and 4: In the diagram use mol and mass percent for compositions and mol and mass for flow as specified.

Step 5: Basis P = 100 lb

Step 6: Unknowns: F, S, W

Step 7: Can make total and 3 component balances: rice, H₂O, dry gas (G)

Steps 8 and 9:

lb Rice: $F(0.75) = P(0.95) = 100(0.95)$

lb mol Dry gas: $S(0.9527) = W(0.9069)$

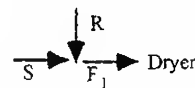
lb mol H₂O H₂O: $S(0.0473) + \frac{F(0.25)}{18.02} = W(0.0931) + \frac{P(0.05)}{18.02}$

Solutions Chapter 12

$$F = 126.67 \text{ lb}$$

$$S = 27.35 \text{ lb mol}$$

$$W = 28.75 \text{ lb mol}$$



Make balances on the mixing point (easiest)

lb mol gas: $(27.35)(0.9527) + R(0.9069) = F_1 x_{DG}^{F_1}$

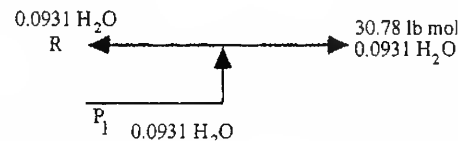
$$x_{H_2O}^{F_1} = 0.0520$$

lb mol H₂O: $(27.35)(0.0473) + R(0.0931) = F_1 x_{H_2O}^{F_1}$

lb mol total: $27.35 + R = F_1$

$$x_{DG}^{F_1} + x_{H_2O}^{F_1} = 1$$

$$R = 3.12 \text{ lb mol} / 100 \text{ lb P}$$



or, make balances on separation point

H₂O: $P_1(0.0931) = R(0.0931) + 30.768(0.0931)$

total (or G): (only 1 independent equation)

$$0.0473 S + 0.0931 R = F_1(0.052)$$

$$27.35 + R = F_1$$

(continued)

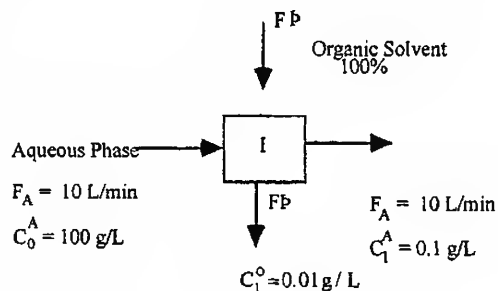
Solutions Chapter 12

$$1.385 + 0.0931 R = 0.052 (27.35 + R) = 1.523 + 0.052R$$

$$0.041 R = 0.138$$

$$R = 3.37 \text{ b mol}$$

12.12



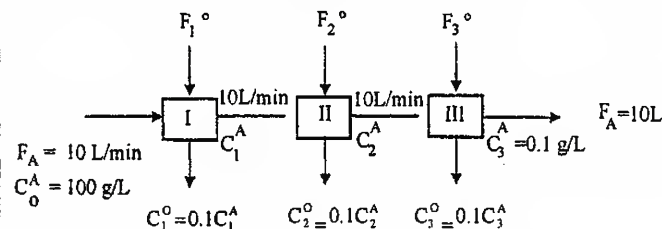
Fermentation product balance:

$$100 \frac{\text{g}}{\text{L}} \cdot 10 \frac{\text{L}}{\text{min}} = F^p (0.01) + 10 \frac{\text{L}}{\text{min}} \cdot 0.1 \frac{\text{g}}{\text{L}}$$

$$F^p = \frac{1000 - 1}{0.01} = 99,900 \frac{\text{L}}{\text{min}}$$

Solutions Chapter 12

b.



Fermentation balance:

Assuming $F_1^o = F_2^o = F_3^o = F^o/3$

$$\text{I: } \frac{100 \frac{\text{g}}{\text{L}}}{10 \frac{\text{L}}{\text{min}}} = C_1^A \cdot 10 \frac{\text{L}}{\text{min}} + \frac{F^o}{3} \times 0.1 C^A \quad (1)$$

$$\text{II: } \frac{C_1^A \frac{\text{g}}{\text{L}}}{10 \frac{\text{L}}{\text{min}}} = C_2^A \cdot 10 \frac{\text{L}}{\text{min}} + \frac{F^o}{3} \times 0.1 C^A \quad (2)$$

$$\text{III: } \frac{C_2^A \frac{\text{g}}{\text{L}}}{10 \frac{\text{L}}{\text{min}}} = C_3^A \cdot 10 \frac{\text{L}}{\text{min}} + \frac{F^o}{3} \times 0.1 C_3^A \quad (3)$$

Solving (1), (2) and (3) Simultaneously

$$C_1^A = 10.0 \frac{\text{g}}{\text{L}} \quad C_2^A = 1.0 \frac{\text{g}}{\text{L}} \quad C_3^A = 0.1 \frac{\text{g}}{\text{L}}$$

$$F = 2702 \frac{\text{L}}{\text{min}}$$

(continued)

Solutions Chapter 12

C:

Fermentation Product Balance:

$$\text{I: } \frac{100 \frac{\text{g}}{\text{L}}}{10 \frac{\text{L}}{\text{min}}} + 0.1 C_2^A \cdot F^\circ = 0.1 C_1^A \cdot F^\circ + C_1^A \cdot 10$$

$$\text{II: } C_1^A \cdot 10 + 0.1(0.1)F^\circ = 0.1 C_2^A \cdot F^\circ + C_2^A \cdot 10$$

$$\text{III: } C_2^A \cdot 10 + 0 = 0.1(0.1) \cdot F^\circ + 0.1(10)$$

Solving (1), (2) and (3) Simultaneously

$$C_1^A = 10.36 \text{ g/L}$$

$$C_2^A = 1.06 \text{ g/L}$$

$$C_3^A = 0.10 \text{ g/L}$$

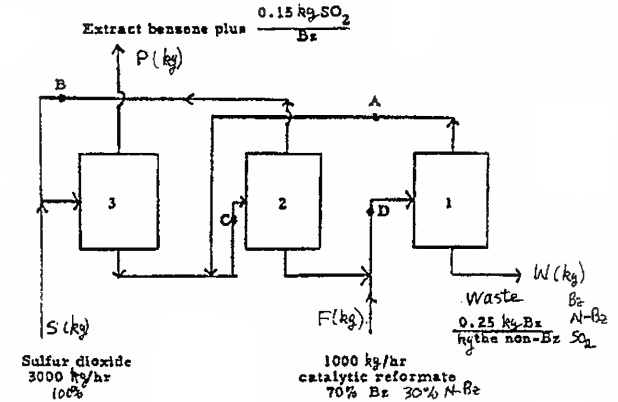
$$F = 960 \frac{\text{L}}{\text{min}}$$

This one is the least

Solutions Chapter 12

12.13

Steps 2, 3, and 4: (Non Bz is non-benzene)



Step 5: Basis: 1 hr

Process is steady state, no reaction

Steps 2, 3 and 4:

Compositions:

$$\begin{aligned} \text{at P} \quad \text{SO}_2 \quad \frac{0.15 \text{ kg SO}_2}{1 + 0.15} &= 0.130 & \text{at W} \quad \left. \begin{array}{l} m_{\text{Bz}}^{\text{II}} \\ m_{\text{NonBz}}^{\text{II}} \\ m_{\text{SO}_2}^{\text{II}} \end{array} \right\} \Sigma = W \\ \text{Bz} \quad 1 - 0.130 &= \frac{0.870}{1.00} \end{aligned}$$

(continued)

Solutions Chapter 12

Pick the overall process as the system

Steps 6 and 7:

Unknowns: $P, 3m_1^w$ (4)

Balances: $Bz, SO_2, \text{non } Bz, m_{Bz}^w/m_{\text{non}Bz}^w = 0.25$ (4)

Steps 8 and 9: Balances are in kg

Total $3000 + 1000 = P + W$

Bz: $1000 (0.70) = P \left(\frac{1.00}{1.15} \right) + m_{Bz}^w$

Non Bz: $1000 (0.30) = P (0) + m_{\text{non}Bz}^w$ $m_{\text{non}Bz}^w = 300 \text{ kg}$

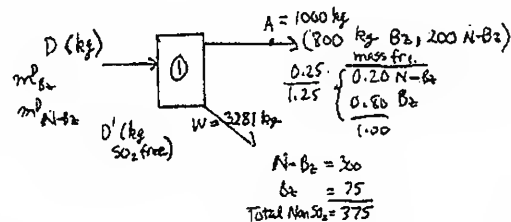
SO_2 : $3000 = P \left(\frac{0.15}{1.15} \right) + m_{SO_2}^w$ $m_{Bz}^w = 300 (0.25) = 75 \text{ kg}$

a. Solution: $P = 719 \text{ kg}$ $m_{SO_2}^w = 2906 \text{ kg}$

$W = 3281 \text{ kg}$

System: Unit 1

Solutions Chapter 12



Steps 6 and 7:

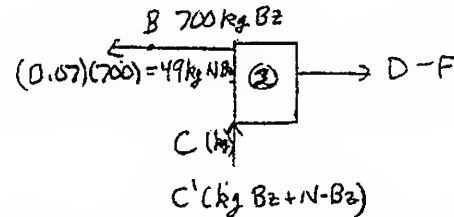
Unknowns: $m_{Bz}^D, m_{\text{non}Bz}^D, m_{SO_2}^D$

Balances: $Bz, \text{non}Bz, SO_2$

Steps 8 and 9: Balances are in kg

b. $Bz + \text{non}Bz: D' = A + 375$ $D' = 1000 + 375 = 1375 \text{ kg}$

System: Unit 2



(continued)

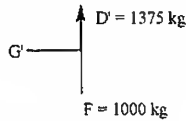
Solutions Chapter 12

Steps 6 and 7:

Steps 8 and 9: Balances are in kg

Bz + nonBz: $C' = 749 + G'$

System: mixing point



$$G' = 1375 - 1000 = 375 \text{ kg}$$

c. $C' = 749 + 375 = \boxed{1124 \text{ kg}}$

12.14

Single pass conversion is: $f_{sp} = \frac{-U_{LR} \xi}{n_{LR}^{\text{reactor feed}}}$

a. Single pass conversion based on H_2 as the limiting reactant:

$$\xi = \frac{1.979 - 3.96}{-2} = 0.99$$

$$\xi^{\text{max}} = \frac{0 - 3.96}{-2} = 1.98$$

$$\text{SP conversion} = \frac{-(-2)(0.99)}{3.96} = \boxed{0.50}$$

Use Eq. (12.1) and Eq. 12.2 with H_2 the limiting reactant

Solutions Chapter 12

b. $0.99 = \frac{-v_{LR} \xi}{n_{LR}^{\text{fresh feed}}} = \frac{-(-2) \xi}{1.98} \quad \xi = 0.980$

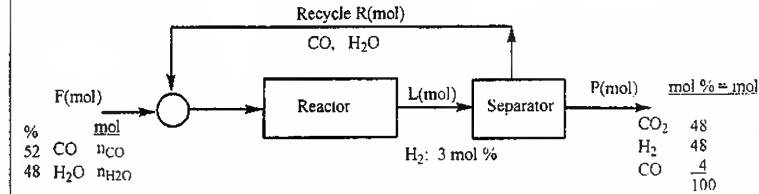
$$f_{sp} = \frac{-(-2)(0.98)}{1.989} = 0.986$$

c. Overall conversion of H_2
 $f_{\text{overall}} \text{ of } H_2 = \frac{-(-2)(0.99)}{1.98} = \boxed{1.0}$

d. Overall conversion of CO
 $f_{\text{overall}} \text{ of } CO = \frac{-(-1)(.99)}{1} = \boxed{0.99}$

12.15

Steps 2, 3, and 4:



Step 5: Basis: $P = 100 \text{ mol}$

Pick the overall process as the system.

Step 6: Unknowns: $n_{CO}^F, n_{H_2O}^F$

Step 7: Balances: C, H, O

Steps 8 and 9: Element balances

(continued)

Solutions Chapter 12

$$\begin{array}{l} \text{C (mol): } n_{\text{CO}} = 48 + 4 = 52 \\ \text{H (mol): } n_{\text{H}_2\text{O}}(2) = 48(2) \quad n_{\text{H}_2\text{O}} = 48 \end{array} \left. \vphantom{\begin{array}{l} \text{C (mol): } n_{\text{CO}} = 48 + 4 = 52 \\ \text{H (mol): } n_{\text{H}_2\text{O}}(2) = 48(2) \quad n_{\text{H}_2\text{O}} = 48 \end{array}} \right\} \text{total 100}$$

Step 10: O (mol): $n_{\text{H}_2\text{O}}(1) + n_{\text{CO}}(1) = 48(2) + 4$ check is ok.

a. Composition of fresh feed 40% H₂O and 52% CO

Alternate solution: Use extent of reaction

Based on CO₂: $\xi = \frac{48-0}{1} = 48$

Then $n_{\text{CO}}^F = 4 + \xi = 4 + 48 = 52 \text{ mol}$
 $n_{\text{H}_2\text{O}}^F = 0 + \xi = 48 \text{ mol}$

To get the recycle, make a balance about the separator (no reaction occurs)

H₂ balance (mol): $L(0.03) = 48 \quad L = 1600 \text{ mol}$

Total (mol): $L = 100 + R \quad R = 1500 \text{ mol}$

b. $\frac{1500 \text{ mol R}}{48 \text{ mol H}_2} = \boxed{31.3}$

12.16

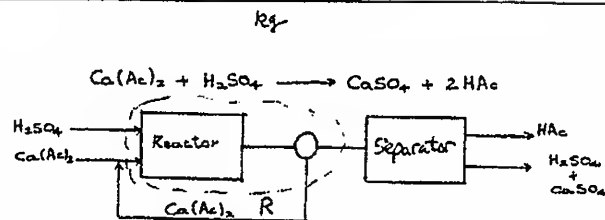
Steps 2, 3, and 4:

MW Ca (Ac)₂ = 158.1 MW HAc = 60

$$\frac{100 \text{ kg Ca(Ac)}_2}{158.1 \text{ kg Ca(Ac)}_2} \left| \frac{1 \text{ kg mol Ca(Ac)}_2}{158.1 \text{ kg Ca(Ac)}_2} \right. = 0.633 \text{ kg mol Ca(Ac)}_2$$

Step 5: Basis: 1000 kg of Ca(Ac)₂ feed

Solutions Chapter 12



Inspection of the diagram shows that the overall conversion of Ca(Ac)₂ is 100% (none leaves the process). Thus, $f_{\text{OA}} = 1$. You are given $f_{\text{SP}} = 0.90$. Then

a. $\frac{f_{\text{SP}}}{f_{\text{OA}}} = \frac{0.90}{1} = \frac{6.33}{6.33 + R}$ $R = 0.703 \text{ kg mol}$
or 111 kg

b. The single pass conversion for Ca(Ac)₂ is 0.90.

$$0.90 = \frac{-v_{\text{LR}} \xi}{n_{\text{LR}}^{\text{feed}}} = \frac{-(-1) \xi}{6.33} \quad \xi = 5.697$$

Overall HAc balance:

$$\frac{6.33 \text{ kg mol Ca (Ac)}_2}{1 \text{ kg mol Ca(Ac)}_2} \left| \frac{2 \text{ kg mol HAc}}{1 \text{ kg mol Ca(Ac)}_2} \right. = 12.66 \text{ kg mol HAc or } \boxed{760 \text{ kg}}$$

12.17

Steps 2, 3, 4:

MW C₂H₂ = 26.02
MW Zn = 65.37

MW C₂H₂Br₄ = 346

(continued)

Solutions Chapter 12

a. C_2H_5 produced per hour

Step 5: Basis: 1 hr = 1000 kg $C_2H_2Br_4$ (2.890 kg mol)

Make overall balances:

Get the extent of reaction using $C_2H_2Br_4$

$$n_{out} - n_{in} = \nu \xi$$

$$0 - 2.890 = (-1)(\xi) \quad \xi = 2.890 \text{ reacting moles}$$

$$C_2H_2 \text{ balance: } n_{C_2H_2} = 0 + (1)(2.890) = 2.890 \text{ kg mol}$$

$$2.890 (26.02) = \boxed{75.2 \text{ kg}}$$

$$ZnBr_2 \text{ balance: } n_{ZnBr_2} = 0 + 2(2.890) = 5.78 \text{ kg mol}$$

Alternate solution

$$\frac{100 \text{ kg } C_2H_2Br_4}{1} \left| \frac{1 \text{ kg mol } C_2H_2Br_4}{346 \text{ kg } C_2H_2Br_4} \right| \frac{1 \text{ kg mol } C_2H_2}{1 \text{ kg mol } C_2H_2Br_4} \left| \frac{26 \text{ kg } C_2H_2}{1 \text{ kg mol } C_2H_2} \right| = 75.2$$

b. Recycle

Make balance on the mixing point. First, get the feed of $C_2H_2Br_4$ to the reactor

$$0.80 = \frac{-\nu \xi}{n_{LR}^{feed}} = \frac{-(-1)(2.896)}{n_{LR}^{feed}} \quad n_{LR}^{feed} = 3.61 \text{ kg mol}$$

$$C_2H_2Br_4 \text{ balance: } 2.890 + R = 3.61 \quad R = 0.72 \text{ kg mol}$$

$$0.72 (346) = \boxed{249 \text{ kg}}$$

Alternate solution (in kg). Balance over separator.

$$(1000 \text{ kg} + R)(0.20) = R$$

$$R = 250 \text{ kg}$$

c. Feed rate required for 20% excess Zn in reactor:

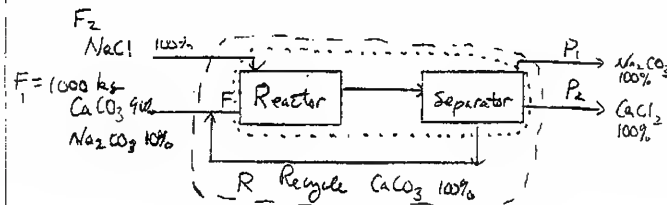
Solutions Chapter 12

$$\frac{1000 \text{ kg } C_2H_2Br_4}{1} \left| \frac{1 \text{ kg mol } C_2H_2Br_4}{346 \text{ kg } C_2H_2Br_4} \right| \frac{2 \text{ kg mol Zn}}{1 \text{ mol } C_2H_2Br_4} \left| \frac{65.37 \text{ kg Zn}}{1 \text{ kg mol Zn}} \right| \frac{1.2 \text{ kg Zn in feed}}{1 \text{ kg Zn required}} = \boxed{454 \text{ kg}}$$

d. Mole ratio of $ZnBr_2$ to C_2H_2 in final products:

$$\frac{5.78}{2.89} = \boxed{2} \quad 2:1 \text{ (as per reaction)}$$

12.18



Step 5:

Basis: 100 kg $F_1 \equiv 1 \text{ hr}$

Overall balance

Step 6 and 7:

Unknowns: F_2, P_1, P_2

Element balances: Ca, Na, Cl, CO_3 (enough, not all independent)

CO_3 balance:

$$\frac{900 \text{ kg } CaCO_3}{1} \left| \frac{1 \text{ kg mol } CaCO_3}{100 \text{ kg } CaCO_3} \right| \frac{1 \text{ kg mol } CO_3}{1 \text{ kg mol } CaCO_3} = 9.00 \text{ kg mol } CO_3$$

(continued)

Solutions Chapter 12

$$\frac{100 \text{ kg Na}_2\text{CO}_3}{106 \text{ kg Na}_2\text{CO}_3} \cdot \frac{1 \text{ kg mol Na}_2\text{CO}_3}{1 \text{ kg mol Na}_2\text{CO}_3} \cdot \frac{1 \text{ kg mol CO}_2}{1 \text{ kg mol Na}_2\text{CO}_3} = 0.94 \text{ kg mol CO}_2$$

$$9.94 \text{ kg mol CO}_2$$

$$a. \frac{9.94 \text{ kg mol CO}_2}{1 \text{ kg CO}_2} \cdot \frac{1 \text{ kg mol Na}_2\text{CO}_3}{1 \text{ kg mol Na}_2\text{CO}_3} \cdot \frac{106 \text{ kg Na}_2\text{CO}_3}{1 \text{ kg mol Na}_2\text{CO}_3} = 1054 \text{ kg Na}_2\text{CO}_3$$

Species balance about the reactor plus the separator on CaCO_3 :

$$\frac{\text{IN}}{\text{UNREACTED}} [1000(0.90) + R] \cdot (24) = R$$

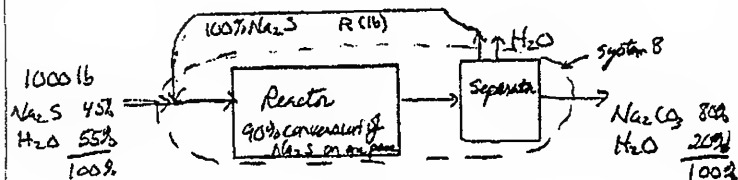
$$R = 284 \text{ kg}$$

Alternate solution:

Use the extent of reaction to get the same results.

12.19

Steps 1, 2, 3, and 4:



Mol. Wt: Na_2S , 78; CaCO_3 , 100; Na_2CO_3 , 106; CaS , 72

Solutions Chapter 12

Step 5: Basis 1 hr

Steps 6, 7, 8, and 9:

System: Overall (System A)

$$\text{Na Balance: } \frac{(1000)(0.45) \text{ lb Na}_2\text{S}}{78 \text{ lb Na}_2\text{S}} \cdot \frac{1 \text{ lb mol Na}_2\text{S}}{1 \text{ lb mol Na}_2\text{S}} \cdot \frac{2 \text{ lb mol Na}}{1 \text{ lb mol Na}_2\text{S}}$$

$$= \frac{m_{\text{Na}_2\text{CO}_3} \text{ lb}}{106 \text{ lb Na}_2\text{CO}_3} \cdot \frac{1 \text{ lb mol Na}_2\text{CO}_3}{1 \text{ lb mol Na}_2\text{CO}_3} \cdot \frac{2 \text{ lb mol Na}}{1 \text{ lb mol Na}_2\text{CO}_3} \cdot \frac{100 \text{ lb Na}_2\text{CO}_3 \text{ soln}}{80 \text{ lb Na}_2\text{CO}_3}$$

$$b. \quad m_{\text{Na}_2\text{CO}_3} = 764 \text{ lb/hr}$$

System: Reactor plus separator (System B)

$$\text{Na}_2\text{S balance: } \frac{\text{in}}{(\text{lb mol})} \left[\frac{100(0.45)}{78} + \frac{R}{78} \right] - \frac{\text{out}}{78} - \frac{\text{gen}}{78} + \frac{\text{Consumption}}{78} = \frac{\text{accum}}{78}$$

$$\left[\frac{100(0.45)}{78} + \frac{R}{78} \right] - \frac{R}{78} + 0 - \left[\frac{100(0.45)}{78} + \frac{R}{78} \right] \cdot 0.90 = 0$$

$$[1000(0.45) + R] (0.10) = R$$

$$a. \quad R = 50 \text{ lb/hr}$$

Alternate solution

Na_2S is the limiting reactant (LR). Mole $\text{Na}_2\text{S} = (0.45)(1000)/78 = 5.77$. All of it reacts.

$$1.00 = \frac{(-1)(-1)\xi}{5.77}, \quad \xi = 5.77$$

(continued)

Solutions Chapter 12

Overall fraction conversion of Na_2S is 100%; $f_{\text{OA}} = 1$.

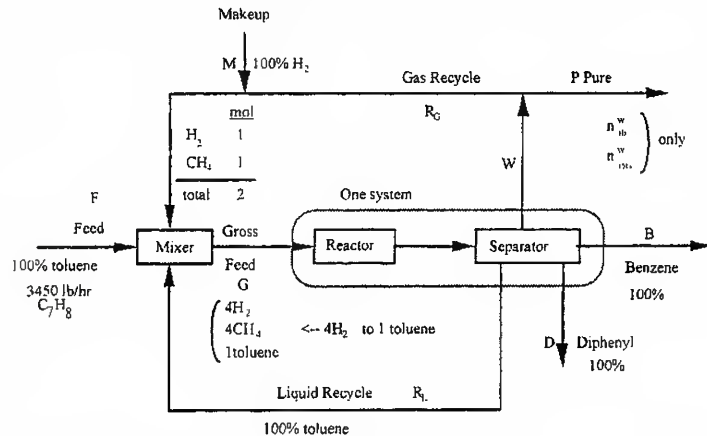
$$\frac{f_{\text{SP}}}{f_{\text{OA}}} = \frac{0.90}{1.00} = \frac{n_{\text{LR}}^{\text{freshfeed}}}{n_{\text{LR}}^{\text{freshfeed}} + n_{\text{LR}}^{\text{recycle}}} = \frac{5.77}{5.77 + R}$$

$$5.19 + 0.9R = 5.77 \quad \boxed{R = 0.64 \text{ lb mol}} \quad (\text{or } 50 \text{ lb})$$

12.20

A basis of 1 hr requires the listing and solution of many simultaneous equations.

A basis of 100 mol of toluene in G is more convenient



Basis: 100 mol toluene in stream G (gross feed)

System: Reactor plus separator

Solutions Chapter 12

Species balances

	In	Out	Gen	Cons.	
(1) toluene:	100	$-R_L$	+0	$-100(.80 + .08)$	= 0
(2) H_2 :	100 (4)	$-n_{\text{H}_2}^w$	+0	$-100(4)(.80 + .08(\frac{1}{2}))$	= 0
(3) CH_4 :	100 (4)	$-n_{\text{CH}_4}^w$	+100(4)(.80 + .08)	-0	= 0
Solve above for		$R_L = 12 \text{ mol}$			
		$n_{\text{H}_2}^w = 64 \text{ mol}$	} Total = 816 mol		
		$n_{\text{CH}_4}^w = 752 \text{ mol}$			

System: Mixer plus makeup point (Species balances but no reaction so In = Out)

	(F)	(M)	(R _G)	(R _L)	(G)
(1) Toluene:	$F(1.0) +$	0	+ 0	+ 12	= 100
(2) H_2 :	0	+ $M(1.0)$	+ $R_G(\frac{64}{816})$	+ 0	= 400
(3) CH_4 :	0	+ 0	+ $R_G(\frac{752}{816})$	+ 0	= 400

Solve (3) for $R_G = 434 \text{ mol}$

Solve (1) for $F = 88 \text{ mol}$ $M = 366$

Change basis to 1 hour

(continued)

Solutions Chapter 12

$$\frac{3450 \text{ lb}}{92 \text{ lb}} \times \frac{1 \text{ lb mol}}{1} = 37.5 \text{ lb mol of toluene in F}$$

$$\frac{100 \text{ lb mol tol in G}}{88 \text{ lb mol F}} \times \frac{37.5 \text{ lb mol F}}{1 \text{ hr}} \times \frac{12 \text{ lb mol R}_L}{100 \text{ lb mol tol in G}} = 5.11 \text{ lb mol R}_L/\text{hr}$$

$$\frac{100}{88} \left| \frac{37.5}{1} \right| \frac{434 \text{ lb mol } R_G}{100 \text{ lb mol tol in } G} = 185 \text{ lb mol } R_G/\text{hr}$$

If $F = 37.5 \text{ lb mol}$ of toluene is selected as the basis, you have to make the same balances as above plus benzene and diphenyl balances on the reactor plus separator because F is a known but G becomes an unknown.

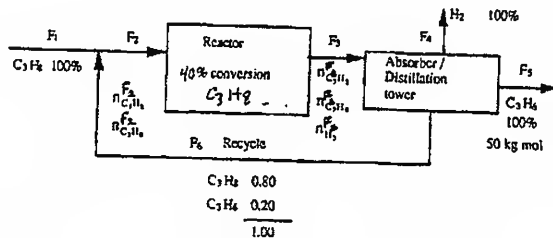
The unknowns would be

$$G, R_L, R_G, D, B, M \text{ и } n_{H_2}^P, n_{CH_4}^P$$

Alternate solution

Calculate the extent of reaction for each reaction, and use them as shown in the book to get the outputs of the reactor plus separator system instead of using generation and consumption terms.

12.21



Solutions Chapter 12

Basis: 1 hr = 50 kg mol F_5

Unknowns:

$$F_1, F_4, F_6, n_{C_2H_8}^{F_2}, n_{C_3H_6}^{F_2}, n_{C_2H_8}^{F_3}, n_{C_3H_6}^{F_3}, n_{H_2}^{F_3} \quad (8)$$

Balances:

Mixing Point:	C_3H_8, C_3H_6	} (8)
Reactor:	C_3H_8, C_3H_6, H_2	
Abs./Distil.:	C_3H_8, C_3H_6, H_2	

Use overall balances as substitute for some of the above

Overall balances (element balances because of the reaction)

$\text{C: } F_1(3) = F_5(3)$
 $\text{H: } F_1(8) = F_4(2) + F_5(6)$
 $8(50) = 2F_4 + 50(6)$

$F_1 = 50 \text{ kg mol}$

$F_4 = 50 \text{ kg mol}$

Mixing point balances (no rxn):

	In	Out
C_3H_8 :	$F_1(1.0) + F_6(0.8) = n_{C_3H_8}^{F_2} = 50 + 0.8F_6$	
C_3H_8 :	$F_1(0) + F_6(0.2) = n_{C_3H_8}^{F_3} = 0.2F_6$	

(continued)

Solutions Chapter 12

Reactor plus absorber/distillation balances:

	In	Out	Generated	Consumed
C_3H_8 :	$n_{C_3H_8}^{F_1}$	$F_6(0.80)$ (recycle)	+ 0	$- 0.4 n_{C_3H_8}^{F_2}$
			$(50 + 0.8F_6) - 0.80 F_6 - 0.4 (50 + 0.8 F_6) = 0$	

Recycle: $F_6 = 93.75$ kg mol

C_3H_8 :	$n_{C_3H_8}^{F_2}$	$F_6(0.20) - 50 +$	$0.40 (50 + 0.8F_6)$	$- 0$	$= 0$
		$n_{C_3H_8}^{F_3} = 18.75$ kg mol			

Note: since $F_2 = F_1 + F_6 = 50 + 93.75 = 143.75$ kg mol (easier calculated this way)
 $n_{C_3H_8}^{F_2} = 0.2, F_6 = 18.75$ kg mol

$F_2 = 18.75 + 125 = 143.75$ kg mol

Omit H_2 balance (Use C_3H_6)

Absorption/distillation tower

C_3H_6 : $n_{C_3H_6}^{F_3} = F_5 = 50$ kgmol

H_2 : $n_{H_2}^{F_3} = F_4 = 50$ kgmol

total: $F_3 = F_4 + F_5 + F_6 = 50 + 50 + 93.75 = 193.75$ kgmol

$n_{C_3H_8}^{F_3} = 193.75 - 100 = 93.75 = F_6$

Summary (all kg mol):

Solutions Chapter 12

$F_1 = 50$	$F_4 = 50$
$F_2 = 143.75$	$F_5 = 50$
$F_3 = 193.75$	$F_6 = 93.75$

(b) 100% (no. C_3H_8 exists)

Alternate solution using extent of reaction

$f_{OA} = 1 = \frac{-1(-1)\xi}{50} \quad \xi = 50$

$f_{SP} = 0.4 = \frac{-1(-1)\xi}{n_{C_3H_8}^{reactor\ feed}} = \frac{50}{n_{C_3H_8}^{F_1}} \quad n_{C_3H_8}^{F_1} = 125$ kg mol

Also $\frac{0.40}{1} = \frac{50}{50 + n_{C_3H_8}^{F_6}}$

$n_{C_3H_8}^{F_6} = 75$ kg mol $n_{C_3H_8}^{F_6} = \frac{0.20}{0.80}(75) = 18.75$ kg mol

$n_{C_3H_8}^{F_2} = 125 = 50 + 0.8 F_6 \quad F_6 = 93.75$

$n_{C_3H_8}^{F_3} = n_{C_3H_8}^{F_2} + 0 = 18.75$

$F_2 = 18.75 + 125 = 143.75$

Similar calculations to these will yield the same results as in the original solution.

12.22

This is steady state process with reaction and recycle. Pick the overall process as the system.

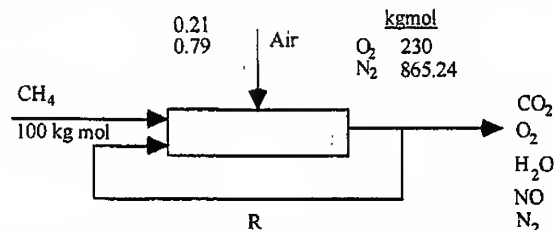
Step 5: Basis: 100 kg mol CH_4

(continued)

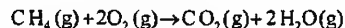
Solutions Chapter 12

Solutions Chapter 12

Steps 1, 2, 3, and 4: The system is as shown in the diagram with recycle added.



Calculate the moles of each component entering.



Calculation of the required O_2 and accompanying N_2 in moles

$$\text{req'd O}_2 \quad 100(2) = 200$$

$$\text{xs} \quad 200(0.15) = 30$$

$$\text{Total O}_2 \quad 230$$

$$\text{N}_2 \text{ in } \left(\frac{230}{0.21} \right) = 865.24$$

The exit concentrations (via stoichiometry) are

	Mol
CO_2	100
O_2	30
H_2O	200
NO	415×10^{-6}
N_2	<u>865.24</u>
	1195.24

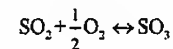
Next, consider adding recycle as shown in the diagram. Recycle is not involved in the overall balance, hence the concentration of NO will not be affected because the extent of reaction with and without recycle remains the same. The recycle does reduce the combustion temperature which in turn will reduce the exit concentration of NO .

12.23

This is a steady state problem with reaction and recycle.

Step 5: Basis: 100 mol F

Steps 1, 2, 3 and 4: Make the overall balances first



	kg mol			Use stoichiometry	Calcd. mol	Calcd. mol fr
SO_2	10.0	F (mol) →	Overall Process	→ P (mol)	$\text{SO}_3 \quad 0.95(10) = 9.50$	0.100
O_2	9.0				$\text{SO}_2 \quad 0.05(10) = 0.50$	0.00525
N_2	81.0				$\text{O}_2 \quad 9-4.75 = 4.25$	0.0446
					<u>$\text{N}_2 \quad 81.0$</u>	0.850
					95.25	1.000

Step 6: The unknowns are the 4 exit compositions plus the extent of reaction if it is to be used.

Steps 7, 8, and 9: We have 3 element balances plus the fraction conversion of the SO_2 to SO_3 , or 4 species balances (SO_3 , SO_2 , N_2 , O_2). We can use a mixture of element and species balances.

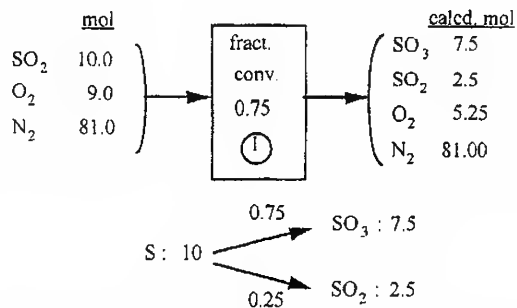
(continued)

Solutions Chapter 12

Element S: $10 = 0.95(10) + 0.05(10)$ check is ok

Compound N_2 : $81.0 = 81.0$

Select unit 1 as the system

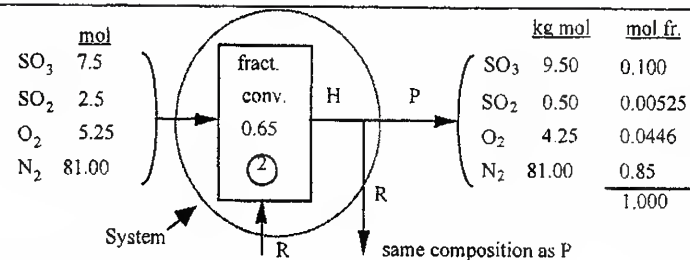


Element 2O: $9.0 + 10.0 = 19 = 1.5(7.5) + 2.5 + n_{O_2} = 11.25 + 2.5 + n_{O_2}$

$$n_{O_2} = 5.25$$

Balance around converter 2 plus separator. Note we need $H = P + R$, and observe that the composition of H, P and R is the same.

Solutions Chapter 12



Make a species balance on SO_2

In	Out	Consumption	Generation
$[2.5 + R(0.00525)]$	$[0.50 + R(0.00525)]$	+0	$-[2.5 + R(0.00525)]0.65 = 0$
$R = 111 \text{ kg mol}$			

12.24

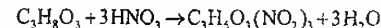
Steady state process with reaction

Step 1, 2, 3, and 4: Get the amount of {reqd., excess} HNO_3 in G.

Step 5: Basis: 1 hr

$$\frac{1 \times 10^3 \text{ kg Glycerine}}{92.11 \text{ kg Gly}} \frac{1 \text{ kg mol Gly}}{92.11 \text{ kg Gly}} = 10.86 \text{ kg mol Gly}$$

Step 4: Glycerine



Required: HNO_3 is 3 (10.86) = 32.58 kg mol (continued)

Solutions Chapter 12

Excess: HNO_3 is $32.56 (20) = 6.516$
 Total: 39.10 kg mol in G

Steps 6 and 7: System is overall

Unknown are F, P, $m_{\text{H}_2\text{SO}_4}^W$, and $m_{\text{H}_2\text{O}}^W$ ($\Sigma m_i = W$)

Equations are: C, H, S, O, N

(or you can use stoichiometry and make species balances, or use the extent of reaction)

C: $10.86 = 0.9650 P$ $P = 11.25 \text{ kg mol or } 11.25 (227.09)$

$$= 2556 \text{ kg}$$

(a)

System is the mixing point

Unknowns: F, $m_{\text{H}_2\text{SO}_4}$, $m_{\text{H}_2\text{O}}$, R, G

(5)

Balances: H_2SO_4 , H_2O , HNO_3 and $m_{\text{H}_2\text{O}} + m_{\text{H}_2\text{SO}_4} + 39.10 = G$ (4)

(a) Glycerine Feed $= \frac{1000}{92.11} = 10.86 \text{ kg mol}$

Nitroglycerine Produced $= \frac{1086 \text{ kg mol}}{1 \text{ lb mol}} \frac{227.98 \text{ kg}}{1 \text{ lb mol}} = 2466 \text{ kg}$

$$0.9650 P = 2465$$

$$P = 2555 \text{ kg}$$

(a)

Solutions Chapter 12

(b) Mol HNO_3 req'd $= \frac{10.86 \text{ mols Glyc.}}{3 \text{ mol HNO}_3} \frac{3 \text{ mol HNO}_3}{\text{mol Glyc}}$

$$= 32.58 \text{ mol}$$

Actual HNO_3 Req'd $= 1200 (32.58) = 39.10 \text{ mol}$

HNO_3 in R $= 39.10 - 32.58 = 6.52 \text{ mol}$

$$= 6.52 (63.01) = 411 \text{ kg}$$

HNO_3 is 70.00% R, $0.7000R = 411$

$$R = 587 \text{ lb}$$

(b)

(c) HNO_3 in G $= 39.10 \text{ mol} = 2464 \text{ kg}$

HNO_3 in R $= 411 \text{ kg}$

$$F + R = G$$

HNO_3 Balance: $F + 411 = 2464$ $F = 2053 \text{ lb HNO}_3$

F is 43.00% HNO_3 so that $0.4300 F = 2053$

$$F = 4774 \text{ lb}$$

(c)

(d) H_2SO_4 in F $= 0.5000 (4774) = 2387 \text{ kg}$

$= \text{H}_2\text{SO}_4$ in W

H_2O in F $= 0.0700 (4774) = 334 \text{ kg}$

H_2O Generated by reaction $= 10.86 \text{ Mole Glyc} \times 3$

$$= (10.86) (3) (18.02) = 587 \text{ kg}$$

H_2O in Stream P $= 0.0350 (2555) = 89 \text{ kg}$

H_2O in W $= \text{H}_2\text{O}$ in F + H_2O generated - H_2O in P (continued)

Solutions Chapter 12

$$= 334 + 587 - 89 = 832 \text{ kg}$$

Component	kg	wt%
H ₂ SO ₄	2387	74.15
H ₂ O	<u>832</u> 3219	<u>25.85</u> 100.00

Stream W = 3219 kg/hr	
H ₂ SO ₄	= 74.15%
H ₂ O	= 25.85%

(d)

Step 10:

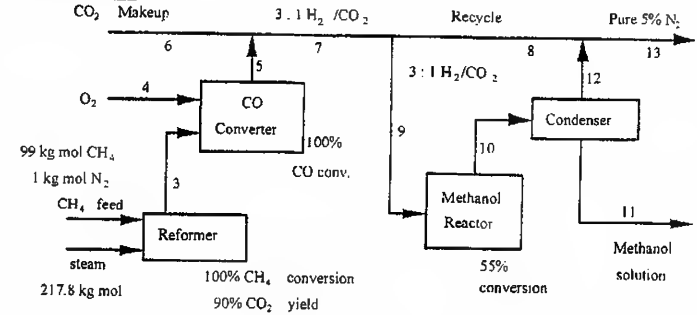
Do numbers check?

Glycerine + F	=	P + W
1000 + 4774	=	2555 + 3219
5774	=	5774

Solutions Chapter 12

12.25

Step 1, 2, 3 and 4:



Chemical Reactions

- $\text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2$ (main reformer rxn)
- $\text{CH}_4 + \text{H}_2 \rightarrow \text{CO} + 3\text{H}_2$ (reformer side rxn)
- $2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2$ (CO converter rxn)
- $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$ (methanol rxn)

CH₄ feed is 1% N₂ or 1 kg mol N₂

steam feed is 10% excess based on reaction (a).

$$99 \text{ kg mol CH}_4 \left(2 \frac{\text{kg mol H}_2\text{O}}{\text{kg mol CH}_4} \right) = 198 \text{ kg mol steam}$$

$$1.1 (198) = 217.8 \text{ kg mol steam}$$

(continued)

Solutions Chapter 12

Step 5: Basis: 100 kg mol CH₄ in feed

Steps 6 and 7: Unknowns:

	6-CO ₂ makeup	10-reactor product
3-reformer product	7-3:1 H ₂ /CO ₂	11-Methanol solution
4-O ₂ feed, stoichiometric	8-recycle, H ₂ /CO ₂ =3	12-condenser tops
5-CO conv. products	9-reactor feed, H ₂ /CO ₂ =3	13-purge, 5% N ₂
<u>Balances:</u>	Reformer balance	Condenser balance
	CO conv. balance	purge/recycle balance
	CO ₂ makeup balance	
	Feed/recycle balance	
	Methanol reactor balance	

Steps 8 and 9: Solve balances serially.

Reformer balance gives stream 3

$$\text{CO}_2 = \frac{99 \text{ kg mol CH}_4 \text{ conv.}}{1 \text{ conv.}} \left| \frac{0.9 \text{ conv by (a)}}{1 \text{ conv.}} \right| \frac{1 \text{ kg mol CO}_2}{1 \text{ kg mol CH}_4} = 89.1 \text{ kg mol CO}_2$$

$$\text{CO} = 99(0.1) = 9.9 \text{ kg mol CO}$$

$$\begin{aligned} \text{H}_2\text{O reacted} &= \frac{2 \text{ kg mol H}_2\text{O}}{1 \text{ kg mol CO}_2} \left| \frac{89.1 \text{ kg mol CO}_2}{1 \text{ kg mol CO}_2} \right| \\ &+ \frac{1 \text{ kg mol H}_2\text{O}}{1 \text{ kg mol CO}} \left| \frac{9.9 \text{ kg mol CO}}{1 \text{ kg mol CO}} \right| = 188.1 \text{ kg mol H}_2\text{O} \end{aligned}$$

Solutions Chapter 12

$$\text{H}_2\text{O remaining} = 217.8 - 188.1 = 29.7 \text{ kg mol H}_2\text{O}$$

$$\text{H}_2 = 4(89.1) + 3(9.9) = 386.1 \text{ kg mol H}_2$$

$$\text{N}_2 = 1 \text{ kg mol}$$

CO conv. balance gives streams 4 & 5:

Stream 4:

$$\text{O}_2 = \frac{9.9 \text{ kg mol CO}}{1 \text{ kg mol CO}} \left| \frac{(1/2) \text{ kg mol O}_2}{1 \text{ kg mol CO}} \right| = 4.95 \text{ kg mol O}_2$$

Stream 5:

$$\text{CO}_2 = 89.1 + 9.9 = 99 \text{ kg mol CO}_2$$

$$\text{H}_2\text{O} = 29.7 \text{ kg mol H}_2\text{O}$$

$$\text{H}_2 = 386.1 \text{ kg mol H}_2$$

$$\text{N}_2 = 1 \text{ kg mol N}_2$$

CO₂ makeup gives streams 6 and 7:

$$\text{stream 7 is } 3:1 \text{ H}_2/\text{CO}_2$$

$$\text{CO}_2 = 386.1/3 = 128.7 \text{ kg mol CO}_2 \text{ needed}$$

$$\text{Stream 6: } \text{CO}_2 = 128.7 - 99 = \boxed{29.7 \text{ kg mol CO}_2}$$

b.

purge/recycle gives stream 13:

(continued)

Solutions Chapter 12

N_2 is inert species:

$$\text{stream 13} = \frac{1.0 \text{ kg mol } N_2}{0.05 \text{ kg mol } N_2 / \text{kg mol stream 13}} = 20 \text{ kg mol in stream 13}$$

Stream 13:

$$H_2/CO_2 = 3 \quad \text{Let } x = \text{mol frac. of } CO_2 \text{ in stream 13}$$

$$1 = 0.05 + 3x + 1x$$

$$4x = 0.95, \quad x = 0.2375$$

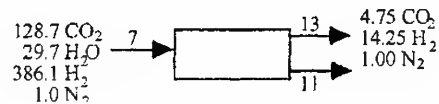
$$N_2 = 1 \text{ kg mol } N_2$$

$$H_2 = 20(3)(0.2375) = \boxed{14.25 \text{ kg mol } H_2}$$

a.

$$CO_2 = 20(0.2375) = 4.75 \text{ kg mol } CO_2$$

Special balance gives stream 11:



1 rxn occurs

$$CO_2 \text{ reacted} = 128.7 - 4.75 = 123.95 \text{ kg mol } CO_2 \text{ reacted}$$

$$H_2 \text{ reacted} = 386.1 - 14.25 = 371.85 \text{ kg mol } H_2 \text{ reacted}$$

$$CH_3OH \text{ produced} = 123.95 \text{ kg mol } CH_3OH$$

$$H_2O \text{ produced} = 123.95 \text{ kg mol } H_2O$$

Solutions Chapter 12

Stream 11:

$$H_2O = 29.7 + 123.95 = 153.65 \text{ kg mol } H_2O$$

$$CH_3OH = 123.95 \text{ kg mol } CH_3OH$$

$$\text{mass stream 11} = 153.65(18) + 123.95(32) = \boxed{6732.1 \text{ kg}}$$

d.

$$\text{wt. \% } CH_3OH = \frac{123.95(32)}{6732.1} = \boxed{58.9\% \text{ } CH_3OH \text{ wt. \%}}$$

Methanol reactor balance for 55% conversion

From special balance, each pass uses 123.95 kg mol CO_2

$$123.95 = 0.55(CO_2)_{in} \quad \text{so } (CO_2)_{in} = 225.36 \text{ kg mol } CO_2$$

$$\text{Stream 8} = \text{stream 9} - \text{stream 7}$$

$$\text{Stream 8: } CO_2 = 225.36 - 128.7 = 95.66$$

$$\text{So } \frac{\text{recycle}}{\text{purge}} = \frac{95.66}{4.75} = \boxed{20.35}$$

c.

12.26

By inspection you can see that the flow of Cl_2 and H_2 in the separator is going the wrong way, hence any calculations make no sense.

12.27

No purge stream exists out of the separator so that CO will build up.

12.28

a. No, they all contain AN and/or NH_3 .

(continued)

Solutions Chapter 12

- b. The bottom stream from the distillation column and the wastewater stream from the condenser are candidates. The bottoms stream from the distillation column contains no NH_3 and has the highest mass fraction of AN of any waste stream so that the entire stream could be fed to the scrubber.
- c. The change in the scrubber feed will not affect any of the stream flows or compositions upstream of the scrubber that are connected to the scrubber, namely those associated with the reactor and the subsequent condenser, nor any downstream flows not connected to the scrubber. A sequential set of material balances can be used to get the flows and concentrations in the rest of the process.

Basis: 1 second

- (1) The water flow rates will not change except for the stream going to treatment, which will be $(10.1 - 0.7) = 9.4 \text{ kg/s}$.
- (2) The AN clues in the streams can be determined from the following balances.

Let x be the kg of AN entering or leaving a particular unit.

Scrubber balance

$$x_{\text{Scrubber}}^{\text{In}} + 4.6 = x_{\text{Decanter}}^{\text{In}}$$

Decanter balance

$$x_{\text{Decanter}}^{\text{In}} = x_{\text{Distill}}^{\text{In}} + 5.5(0.073)$$

Distillation column plus two condenser plus stream jet plus product stream balance

$$x_{\text{Distill}}^{\text{In}} + 0 = x_{\text{Jet}}^{\text{Out}} + x_{\text{Product}}^{\text{Out}} + x_{\text{Scrubber}}^{\text{In}}$$

Distribution of AN entering the distillation column

$$\frac{x_{\text{Jet}}^{\text{Out}}}{x_{\text{Distill}}^{\text{In}}} = \frac{0.2}{4.2} \quad \frac{x_{\text{Product}}^{\text{Out}}}{x_{\text{Distill}}^{\text{In}}} = \frac{3.9}{4.2} \quad \frac{x_{\text{Scrub}}^{\text{In}}}{x_{\text{Distill}}^{\text{In}}} = \frac{0.1}{4.2}$$

Solutions Chapter 12

One of these relations is redundant with the distillation column balance.

The solution of these equations is in kg (note the changes are quite small, hence the number of significant figures is exaggerated):

$$x_{\text{Distill}}^{\text{In}} = 4.302 \quad x_{\text{Scrub}}^{\text{In}} = 0.102 \quad x_{\text{Decant}}^{\text{In}} = x_{\text{Jet}}^{\text{Out}} = 0.205 \quad x_{\text{Prod}}^{\text{Out}} = 3.995$$

Because the changes are so small, the NH_3 concentration changes are negligible.

Solutions Chapter 13

13.1

$$n = \frac{pV}{RT} = \frac{15.5 \text{ mm Hg}}{760 \text{ mm Hg}} \left| \frac{14.7 \text{ psia}}{10.73 \frac{\text{psia ft}^3}{(\text{lb mol}) (^\circ\text{R})}} \right| \frac{100 \text{ ft}^3}{(296)(1.8)^\circ\text{R}}$$

$$n = \frac{(15.5)(14.7)(100)}{(760)(10.73)(533)} = 0.00524 \text{ lb mol}$$

$$\text{lb H}_2\text{O} = (0.00524)(18) = \boxed{0.0944 \text{ lb H}_2\text{O}}$$

13.2

Basis: 1 L gas at 780 mm Hg and T

$$\frac{1\text{L}}{760 \text{ mm Hg}} \left| \frac{780 \text{ mm Hg}}{760 \text{ mm Hg}} \right| = \boxed{1.026 \text{ L}}$$

13.3

$$(pV)_1 = (pV)_2$$

$$1 \times 1 = p \times 1.2$$

$$p = \frac{1}{1.2} = \boxed{0.83 \text{ atm}}$$

13.4

Specific volume: MW = molecular weight

$$\hat{V} = \frac{(R)(T)}{p} = \frac{(\bar{R}/\text{MW})T}{p} = \frac{(1545.3/28.97)(78 + 460)}{(14.7)(144)} = 13.56 \text{ ft}^3/\text{lb}_m$$

Molal specific volume:

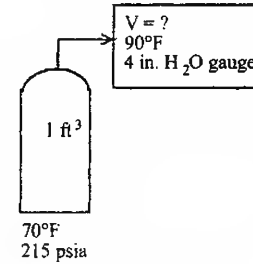
Solutions Chapter 13

$$\hat{V}_m = \frac{(\bar{R})(T)}{p} = \frac{(1545.3)(78 + 460)}{(14.7)(144)} = 392.8 \text{ ft}^3/\text{lb mol}$$

Note that

$$\hat{V} = \frac{\hat{V}_m}{\text{MW}} = \frac{392.8}{28.97} = 13.56 \text{ ft}^3/\text{lb}_m$$

13.5



$$460 + 70 = 530^\circ\text{R}$$

$$460 + 90 = 550^\circ\text{R}$$

atmospheric pressure = 29.92 in. Hg = std atm = 14.7 psia

$$\text{initial pressure} = \frac{200 \text{ psig} + 14.7 \text{ psia}}{14.7 \text{ psia}} \left| \frac{29.92 \text{ in. Hg}}{29.92 \text{ in. Hg}} \right| = 437 \text{ in. Hg}$$

$$\text{final pressure} = 29.92 \text{ in. Hg} + \frac{4 \text{ in. H}_2\text{O}}{12 \text{ in. H}_2\text{O}} \left| \frac{29.92 \text{ in. Hg}}{33.91 \text{ ft H}_2\text{O}} \right|$$

(continued)

Solutions Chapter 13

$$= 29.92 + 0.29 = 30.21 \text{ in. Hg}$$

Basis: 1 ft³ of oxygen at 70°F and 200 psig

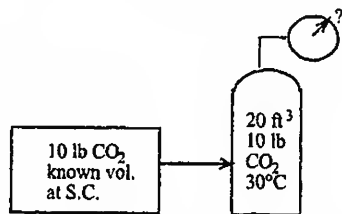
$$\text{final volume} = \frac{1.00 \text{ ft}^3}{530^\circ\text{R}} \left| \frac{550^\circ\text{R}}{30.21 \text{ in. Hg}} \right| \frac{437 \text{ in. Hg}}{530^\circ\text{R}}$$

$$= 15.0 \text{ ft}^3 \text{ at } 90^\circ\text{F and 4 in. H}_2\text{O gauge}$$

Formally, the same calculation can be made using

$$V_2 = V_1 \left(\frac{p_1}{p_2} \right) \left(\frac{T_2}{T_1} \right) \quad \text{since } n_1 = n_2$$

13.6



Solution

We can write (the subscript 1 stands for standard conditions, 2 for the conditions in the tank)

$$p_2 = p_1 \left(\frac{V_1}{V_2} \right) \left(\frac{T_2}{T_1} \right)$$

Solutions Chapter 13

$$\frac{14.7 \text{ psia}}{V_1} \left| \frac{10 \text{ lb CO}_2}{44 \text{ lb CO}_2} \right| \frac{1 \text{ lb mol CO}_2}{1 \text{ lb mol}} \left| \frac{359 \text{ ft}^3}{20 \text{ ft}^3} \right| \frac{303 \text{ K}}{273 \text{ K}} = p_2 = 66.6 \text{ psia}$$

Hence the gauge on the tank will read (assuming that it reads gauge pressure and that the barometer reads 14.7 psia) $66.6 - 14.7 = 51.9 \text{ psig}$

13.7

Assume $\rho_{\text{H}_2\text{O}} = 62.4 \text{ lb/ft}^3$, $p_{\text{bar}} = 14.696 \text{ psia}$

$$p = \frac{500 \text{ ft H}_2\text{O}}{33.91 \text{ ft H}_2\text{O}} \left| \frac{14.696 \text{ psia}}{1} \right| + 14.696 \text{ psia} = 231.387 \text{ psia}$$

$$\dot{V} = \frac{359 \text{ ft}^3}{\text{lb mol}} \left| \frac{14.696}{231.387} \right| \frac{45 + 460}{32 + 460} = 23.4 \frac{\text{ft}^3}{\text{lb mol}}$$

13.8

$$pV = nRT$$

$$T = \frac{pV}{nR} = \frac{121 \text{ kPa}}{0.0011 \text{ kg mol}} \left| \frac{25 \text{ L}}{1000 \text{ L}} \right| \frac{1 \text{ m}^3}{(\text{kg mol})(\text{K})} \left| \frac{8.314 \text{ (kPa)(m}^3\text{)}}{1} \right|$$

$$= 330.8 \rightarrow 331 \text{ K}$$

13.9

You must first convert the temperatures and pressures into absolute units:

$$460 + 70 = 530^{\circ}\text{R}$$

$$460 + 75 = 535^{\circ}\text{R}$$

atmospheric pressure = 29.99 in. Hg = 14.73 psia

$$\text{final pressure} = 29.99 \text{ in. Hg} + \frac{4 \text{ in. H}_2\text{O}}{12 \text{ in. H}_2\text{O}} \left| \frac{29.92 \text{ in. Hg}}{33.91 \text{ ft H}_2\text{O}} \right|$$

$$= 29.99 + 0.29 = 30.28 \text{ in. Hg absolute}$$

The simplest way to proceed, now that the data are in good order, is to apply the ideal gas law. Take as a basis, 16.01 ft³ (do not forget to include the volume of the O₂ tank in your system) of O₂ at 75°F and 30.28 in. Hg. Determine the initial pressure in the O₂ tank alone.

$$p_1 = p_2 \left(\frac{V_2}{V_1} \right) \left(\frac{n_1}{n_2} \right) \left(\frac{T_1}{T_2} \right)$$

$$p_1 = 30.28 \text{ in. Hg} \left(\frac{16.01 \text{ ft}^3}{1 \text{ ft}^3} \right) \left(\frac{530^{\circ}\text{R}}{535^{\circ}\text{R}} \right) = 480 \text{ in. Hg absolute}$$

In gauge pressure,

$$p_1 = \frac{(480 - 29.99) \text{ in. Hg}}{29.92 \text{ in. Hg}} \left| \frac{14.696 \text{ psia}}{29.92 \text{ in. Hg}} \right| = \boxed{221 \text{ psig}}$$

13.10

Basis: Data in the diagram

State 1 is before corking; state 2 is after equilibrium is reached after filling. Assume $p_A = p_{Z1} = 29.92 \text{ in. Hg abs.}$ $p_{Z2} = p_A + \rho_{\text{Hg}}gh = 29.92 + h$ where p_{Z2} is in inches Hg.

Use the ideal gas law: $p_{Z2} V_{Z2} = p_{Z1} V_{Z1}$

$$p_{Z2} = 29.92 (8/6) = 39.89 \text{ in. Hg}$$

$$39.89 = 29.92 + h \quad \text{or} \quad h = 9.97 \text{ in. Hg}$$

$$9.97 + 14 = \boxed{24 \text{ in. Hg}}$$

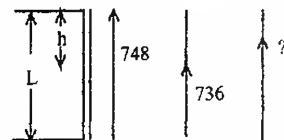
13.11

Basis: fixed amount of air in manometer

A = area of manometer

h = height of air, mm

L = length of manometer, mm



$$p_1 = 755 \quad p_2 = 740 \quad p_3 = 760$$

$$V_{\text{air}} = (h)(A)$$

$$\frac{p_1}{p_2} = \frac{V_2}{V_1} = \frac{h_2}{h_1}$$

$$p_1 = 755 - 748 = 7 \text{ mm Hg} \quad L = 748 + h_1 \quad (1)$$

$$p_2 = 740 - 736 = 4 \text{ mm Hg} \quad L = 736 + h_2 \quad (2) \quad 7Ah_1 = 4Ah_2 \quad (\text{continued})$$

Solutions Chapter 13

$$p_3 = 760 - (L - h_3) \quad \overline{12 + h_1 = h_2} \quad (3) \quad (h_2/h_1) = 7/4 \quad (4)$$

Solving (3) and (4): $h_1 = 16 \text{ mm}$ $L = 764 \text{ mm}$

$$7(A)(h_1) = [760 - (L - h_3)](A)(h_3) \quad (5)$$

Substituting values of h_1 , L in (5), one obtains:

$$h_3 = 18 \text{ mm}$$

The height of barometer = $L - h_3 = \boxed{751 \text{ mm Hg}}$

13.12

Basis: 5 L at 1 atm and T

Assume T is constant throughout the dive.

At the end of the dive the pressure is $p = \rho gh$, or easier let $x = \text{depth in m}$.

$$\frac{x \text{ m}}{10.34} \left| \frac{1 \text{ atm}}{10.34} \right| + 1 = p \text{ atm}$$

The pressure for 1 L is obtained from $p_1 V_1 = p_2 V_2$

$$p_2 = p_1 \left(\frac{V_1}{V_2} \right) = 1 \text{ atm} \left(\frac{5 \text{ L}}{1 \text{ L}} \right) = 5 \text{ atm}$$

$$\frac{x}{10.34} = 4 \quad \text{hence } x = \boxed{41.4 \text{ m}}$$

Solutions Chapter 13

13.13

Basis: air at 30 psi and 75°F in volume of tire

(1) Initial State (2) Final State

$$p_1 = 44.7 \text{ psia}$$

$$p_2 = ?$$

$$T_1 = 535^\circ \text{R}$$

$$T_2 = 600^\circ \text{R}$$

$$V_1 = ?$$

$$V_2 = ?$$

$$N_1 = ?$$

$$N_2 = ?$$

$$\frac{p_1 V_1}{p_2 V_2} = \left(\frac{n_1}{n_2} \right) \frac{R}{R} \left(\frac{T_1}{T_2} \right)$$

Assume volume is the same
The number of mols are the same $\left\{ p_2 = p_1 \left(\frac{T_2}{T_1} \right) = (44.7) \left(\frac{600}{535} \right) = 50.2 \text{ psia} \right.$

$$50.2 - 14.7 = 35.5 \text{ psia}$$

just over the limit

13.14

Basis: 1 hr

a) $Q = v A$

$$Q = \frac{11.3 \text{ ft}}{\text{s}} \left| \frac{3600 \text{ s}}{1 \text{ hr}} \right| \frac{(18.0 \text{ in})^2}{(12 \text{ in})^2} \left| \frac{1 \text{ ft}^2}{144 \text{ in}^2} \right| \pi = 2.875 \times 10^5 \frac{\text{ft}^3}{\text{hr}}$$

$$\text{In } 1.0 \text{ hr } \boxed{2.875 \times 10^5 \text{ ft}^3}$$

b) $m = \rho v s$

(continued)

Solutions Chapter 13

$$m = 0.0796 \frac{\text{lb}_m}{\text{ft}^3} \left| \frac{11.3 \text{ ft}}{\text{s}} \right| \pi \left| \frac{(18.0)^2 \text{ in}^2}{(12 \text{ in})^2} \right| \frac{1 \text{ ft}^2}{\text{in}^2} = 6.358 \frac{\text{lb}_m}{\text{s}}$$

$$\text{In 1 day: } \frac{6.358 \text{ lb}_m}{\text{s}} \left| \frac{3600 \text{ s}}{1 \text{ hr}} \right| \frac{24 \text{ hr}}{1} = \boxed{5.49 \times 10^5 \text{ lb}_m}$$

13.15 Basis: Flue gas at 1800°F, constant pressure, and given volume

1. Calculate the inlet cross-sectional area
- A_i
- :

$$A_i = \pi[(D_i)^2]/4 = \pi(4^2)/4 = 12.57 \text{ ft}^2$$

2. Calculate the inlet volumetric flow rate
- Q
- :

$$Q = (\text{velocity}) \times (\text{cross-sectional area}) = 25(12.57) = 314.16 \text{ ft}^3/\text{s}$$

3. Calculate the outlet volumetric flow rate using the ideal gas law:

$$Q_o = Q_i(T_o/T_i) = 314.16(460 + 550)/(460 + 1800) = 140.40 \text{ ft}^3/\text{s}$$

4. Calculate the outlet cross-sectional area:

$$A_o = Q_o/v_o = 140.40/20 = 7.02 \text{ ft}^2$$

5. Calculate the outlet duct diameter:

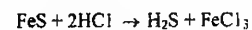
$$(D_o)^2 = 4(A_o)/\pi = 4(7.02)/\pi$$

$$D_o = (4(7.02)/\pi)^{0.5} = \boxed{2.99 \text{ ft}}$$

Solutions Chapter 13

13.16

Basis: 10 kg FeS (MW = 87.9)



$$\frac{10 \text{ kg FeS}}{1} \left| \frac{1 \text{ kg mol FeS}}{87.9 \text{ kg FeS}} \right| = 0.114 \text{ kg mol FeS}$$

Assume pressure most likely is gage. Absolute pressure = 15.71 + 76.0 = 91.71 cm Hg = 122.2 kPa

$$V = \frac{nRT}{p} = \frac{0.114 \text{ kg mol FeS}}{1} \left| \frac{8.314 (\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})} \right| \frac{(30 + 273)\text{K}}{122.2 \text{ kPa}}$$

$$= \boxed{2.35 \text{ m}^3 \text{ @ } 30^\circ\text{C and } 15.71 \text{ cm Hg gauge}}$$

13.17Apply $pV = nRT$ twice or use it once with R

$$\text{Basis: 1 pound mole fg} \quad \frac{V}{n} = \frac{(0.7302)(560)}{1.54}$$

(1) 100°F (560°R) and 1.54 atm

(2) 32°F (492°R) and 1 atm (SC)

$$\frac{p_1 V_1}{p_2 V_2} = \frac{T_1}{T_2} \text{ so } V_1 = V_2 \left(\frac{T_1}{T_2} \right) \left(\frac{p_2}{p_1} \right)$$

$$= \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \left| \frac{560^\circ\text{R}}{492^\circ\text{R}} \right| \frac{1 \text{ atm}}{1.54 \text{ atm}} = \boxed{265 \text{ ft}^3 \text{ lb mol}}$$

Solutions Chapter 13

13.18

Basis: 1 hr = 500 lb waste (W)

Get $\mu\text{g}/\text{ft}^3$ at SC 1 $\mu\text{g}/\text{mL} = 0.001 \text{ g/L}$; ignore HC in totaling W

$$\frac{500 \text{ lb W}}{1 \text{ lb}} \left| \frac{454 \text{ g}}{1 \text{ lb}} \right| \left| \frac{0.01 \text{ g HC}}{1 \text{ g W}} \right| \left| \frac{1}{427,000 \text{ ft}^3 \text{ SC}} \right| = 5.32 \times 10^{-3} \text{ g HC/ft}^3 \text{ SC}$$

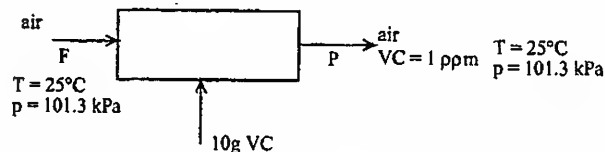
The minimum volume of flue gas is

$$\text{a. } \frac{1 \text{ ft}^3 \text{ SC}}{5.32 \times 10^{-3} \text{ g HC}} \left| \frac{1 \text{ g}}{10^6 \mu\text{g}} \right| \left| \frac{10 \mu\text{g}}{1 \text{ mL}} \right| \left| \frac{25 \text{ mL}}{1} \right| = \boxed{0.047 \text{ ft}^3 \text{ SC}}$$

$$\text{b. } \frac{0.047 \text{ ft}^3 \text{ SC}}{427,000 \text{ ft}^3 \text{ SC}} \left| \frac{1 \text{ hr}}{1} \right| = \boxed{1.1 \times 10^{-7} \text{ hr}}$$

13.19

Basis: 1 min = 10 g VC



Solutions Chapter 13

Apply $pV = nRT$ to get the volume of VC at SC and then use the mole fraction information to get the volume of air (the addition of VC to air has negligible effect on the volume)

MW VC = 78

$$V_{VC} = \frac{n_{VC}RT}{p} = \frac{0.0101 \text{ kg VC}}{1 \text{ lb}} \left| \frac{1 \text{ kg mol VC}}{78 \text{ kg VC}} \right| \left| \frac{8.314 \text{ (kPa)}(\text{m}^3)}{(\text{kg mol})(\text{K})} \right| \left| \frac{298 \text{ K}}{101.3 \text{ kPa}} \right|$$

$$= 3.01 \times 10^{-3} \text{ m}^3 \text{ VC at SC}$$

Volume fraction is the same as mole fraction here.

$$\frac{3.01 \times 10^{-3} \text{ m}^3 \text{ VC at SC}}{1 \text{ m}^3 \text{ VC}} \left| \frac{10^6 \text{ m}^3 \text{ air}}{1 \text{ m}^3 \text{ VC}} \right| = \boxed{3.01 \times 10^3 \text{ m}^3/\text{min}} \text{ an absurd number!}$$

$$(1.06 \times 10^6) \text{ ft}^3/\text{min}$$

If a hood is used:

$$\text{area} = \frac{(30)(25) \text{ in}^2}{144 \text{ in}^2} \left| \frac{1 \text{ ft}^2}{1} \right| \left| \frac{100 \text{ ft}}{1} \right| \left| \frac{(0.3048 \text{ m})^3}{1 \text{ ft}} \right| \times \frac{60 \text{ s}}{\text{min}}$$

$$= \boxed{882 \text{ m}^3/\text{min}} \text{ a smaller amount of air.}$$

Besides inconvenience, the discharge concentration from the hood vent may be unacceptable.

Solutions Chapter 13

13.20

Basis: 100 ppm of TCE (MW 131.5) in air

$$\rho = \frac{p \overline{MW}}{RT} \text{ where } \overline{MW} \text{ is the average MW. At 100 ppm, } \overline{MW} =$$

$$(100 \times 10^{-6})(131.5) + (1 - 100 \times 10^{-6})(29) = 29.013$$

The density is essentially the same as that of air.

13.21

Basis: 1 min

$$T = (68 + 460)/1.8 = 293K$$

$$MW = \text{benzene} = 78.11 \text{ g/g mol} \quad \rho_{Bz \text{ liq}} = 0.879 \text{ g/cm}^3$$

$$pV = nRT \quad R = 0.08206 \text{ (L)(atm)/(g mol)(K)}$$

$$n = \frac{2.5 \text{ cm}^3 \text{ liq}}{\text{min}} \left| \frac{0.879 \text{ g Bz liq}}{1 \text{ cm}^3} \right| \left| \frac{1 \text{ g mol Bz}}{78.11 \text{ g Bz}} \right| = 0.281 \frac{\text{g mol}}{\text{min}}$$

$$V = \frac{0.0281 \text{ g mol}}{\text{min}} \left| \frac{0.08206 \text{ (L)(atm)}}{(\text{g mol})(K)} \right| \left| \frac{293K}{(740/760) \text{ atm}} \right| = 0.694 \frac{\text{L}}{\text{min}}$$

To dilute to 1.0 ppm, multiply by 10^6 or use $6.94 \times 10^5 \text{ L/min}$ ($695 \text{ m}^3/\text{min}$ or $24,500 \text{ ft}^3/\text{min}$).

Solutions Chapter 13

13.22

Basis: 1 m³ gas passing at 10°F and 1 atm. vs 60°F and 1 atm.

(assume $p_1 = p_2$), $T_1 = 520^\circ R$; $T_2 = 470^\circ R$

$$\frac{1 \text{ m}^3}{470^\circ R} \left| \frac{520^\circ R}{470^\circ R} \right| = 1.106 \text{ m}^3$$

Since the moles, and mass, are directly proportional to volume at constant pressure, % increase = 10.6%.

13.23

Basis: CO₂ in cylinder

Volume of cylinder

$$\pi r^2 h = \pi \left(\frac{0.75}{4} \right)^2 (4.33) = 1.91 \text{ ft}^3$$

Assume 100% CO₂ in cylinder at 0°C

$$\frac{1.91 \text{ ft}^3}{14.7 \text{ psia}} \left| \frac{82.6 \text{ psia}}{14.7 \text{ psia}} \right| \left| \frac{530^\circ R}{492^\circ R} \right| = 11.55 \text{ ft}^3 \text{ at } 14.7 \text{ psia, } 70^\circ F$$

If the machine has a 4 gal capacity

$$\frac{4 \text{ gal}}{7.48 \text{ gal}} \left| \frac{1 \text{ ft}^3}{7.48 \text{ gal}} \right| = 0.535 \text{ ft}^3 \text{ at } 14.7 \text{ psia and } 70^\circ F$$

You have more than enough CO₂ to fill the machine, if it operates under atmospheric pressure.

Solutions Chapter 13

13.24

(a) $1.987 \text{ cal}/(\text{g mol})(\text{K})$; (b) $1.987 \text{ Btu}/(\text{lb mol})(^\circ\text{R})$

(c) $\frac{14.7 \text{ psia}}{492^\circ\text{R}} \left| \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \right| = 10.73 (\text{psia})(\text{ft}^3)/(\text{lb mol})(^\circ\text{R})$

(d) $\frac{1.013 \times 10^5 \text{ N/m}^2}{273 \text{ K}} \left| \frac{22.4 \text{ m}^3}{1 \text{ kg mol}} \right| \left| \frac{1 \text{ J}}{1 (\text{N})(\text{m})} \right| \left| \frac{1 \text{ kg mol}}{10^3 \text{ g mol}} \right|$
 $= 8.314 \text{ J}/(\text{g mol})(\text{K})$

(e) $\frac{1 \text{ atm}}{273 \text{ K}} \left| \frac{22,400 \text{ cm}^3}{1 \text{ g mol}} \right| = 82.06 (\text{cm}^3)/(\text{g mol})(\text{K})$

(f) $\frac{1 \text{ atm}}{492^\circ\text{R}} \left| \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \right| = 0.7302 (\text{ft}^3)/(\text{lb mol})(^\circ\text{R})$

13.25

Basis: 1 ft³ O₂ at 100°F, 740 mm Hg

$n = \frac{(740)(14.7)(1)}{(760)(10.73)(560^\circ\text{R})} = 0.00238 \text{ lb mol}$

Density at 100°F, 740 mm Hg

$\rho = \frac{(0.00238)(32)}{1} = \frac{0.0761 \text{ lb/ft}^3}{(1.22 \text{ g/liter})}$

Solutions Chapter 13

13.26

Basis: 1 kg mol gas at 200 kPa and 40°C

(a)

$R = 8.31 \frac{(\text{kPa})(\text{m}^3)}{(\text{K})(\text{kg mol})}$ $T = 40 + 273 = 313 \text{ K}$

$MW = 44 \text{ kg/kg mol}$ $p = 200 \text{ kPa}$

Density = $p(MW)/RT$

$= \frac{200 \text{ kPa}}{313 \text{ K}} \left| \frac{44 \text{ kg}}{1 \text{ kg mol}} \right| \frac{1}{8.31 \frac{(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}} = 3.38 \text{ kg/m}^3$

(b) Specific gravity here is assumed to be density of propane at SC/density of air at SC.

$\text{Sp. gr.} = \frac{p_{\text{C}_3\text{H}_8} n (MW_{\text{C}_3\text{H}_8})}{RT_{\text{C}_3\text{H}_8}} \left| \frac{p_{\text{air}} n (MW_{\text{air}})}{RT_{\text{air}}} \right| = \frac{MW_{\text{C}_3\text{H}_8}}{MW_{\text{air}}} = \frac{44}{29} = 1.52$

13.27

Basis: 1 lb mol gas at 760 mm Hg and 60°F

$\text{Sp. gr.} = \frac{p_{\text{C}_3\text{H}_8} (MW_{\text{C}_3\text{H}_8})}{RT_{\text{C}_3\text{H}_8}} \left| \frac{p_{\text{air}} (MW_{\text{air}})}{RT_{\text{air}}} \right| = \frac{800(44)}{560} \left| \frac{520}{760} \right| \frac{1}{29} = 1.483$

Solutions Chapter 13

13.28

Basis: 1 m³ H₂ at 5°C and 110 kPa

$$a. \frac{1 \text{ m}^3}{273} \left| \frac{273}{278} \right| \frac{110 \text{ kPa}}{101.3 \text{ kPa}} \left| \frac{1 \text{ kg mol}}{22.4 \text{ m}^3} \right| \frac{2 \text{ kg}}{1 \text{ kg mol}} = \boxed{0.0952 \text{ kg/m}^3}$$

$$b. \frac{2 \text{ kg H}_2}{1 \text{ kg mol H}_2} \left| \frac{1 \text{ kg mol air}}{29 \text{ kg air}} \right| = \boxed{0.069} = \text{specific gravity}$$

13.29

Basis: 100 kg mol gas.

		<u>Mol</u>	<u>MW</u>	<u>kg</u>	<u>wt%</u>
a)	CH ₄	87	16	1392	77.5
	C ₂ H ₆	12	30	360	20.0
	C ₃ H ₈	1	44	44	2.5
Total		100		1796	100.0

b) composition in vol. percent = mol percent

CH₄ 87%

C₂H₆ 12%

C₃H₈ 1%

$$c) \text{ MW of gas} = \frac{1796 \text{ kg}}{100 \text{ kg mol}} = 17.96 \frac{\text{kg}}{\text{kg mol}}$$

$$R = 8.314 \text{ (kPa)(m}^3\text{)/(kg mol)(K)} \quad T = 9^\circ\text{C} = 282.15\text{K}$$

Solutions Chapter 13

$$\text{no. of moles of gas} = \frac{80 \text{ kg}}{17.96 \frac{\text{kg}}{\text{kg mol}}} = 4.45 \text{ kg mol}$$

$$V = \frac{nRT}{p} = \frac{4.45 \text{ kg mol} \left| \frac{8.314 \text{ (kPa)(m}^3\text{)}}{(\text{kg mol})(\text{K})} \right| \frac{282.15 \text{ K}}{600 \text{ kPa}}}{1} = \boxed{17.4 \text{ m}^3}$$

$$d) \text{ density} = \frac{17.96 \text{ kg}}{1 \text{ kg mol}} \left| \frac{1 \text{ kg mol}}{22.415 \text{ m}^3 \text{ at SC}} \right| = 0.801 \text{ kg/m}^3$$

$$e) \text{ Specific gravity} = \frac{\text{density of gas at } 9^\circ\text{C and } 600 \text{ kPa}}{\text{density of gas at SC}}$$

$$\frac{600}{8.314} \left| \frac{1}{282} \right| \frac{17.96}{273}$$

$$\frac{101.3}{8.314} \left| \frac{29}{273} \right|$$

$$= \boxed{3.55 \frac{\text{kg/m}^3 \text{ gas at } 9^\circ\text{C, } 600 \text{ kPa}}{\text{kg/m}^3 \text{ gas at SC}}}$$

Solutions Chapter 13

13.30

Basis: 100 mol mixture

a.

Comp	Mol	Mol. Wt.	lb	Wt %
Air	99	29	2870	94.72
Br ₂	1	159.8	160	5.28
	100		3030	100.00

b.
$$\text{Avg. Mol. Wt.} = \frac{3030}{100} = 30.3 \frac{\text{lb}}{\text{lb mol}}$$

c.
$$\text{sp.gr. at SC} = \frac{30.30}{29} = 1.045$$

d.
$$\text{sp.gr.} = \frac{30.30}{159.8} = 0.1895$$

e.
$$\text{sp.gr.} = \frac{\frac{(30.3)}{(359)} \left| \frac{(492)}{(560)} \right| \left| \frac{(114.7)}{(14.7)} \right|}{\frac{(29)}{(359)} \left| \frac{492}{520} \right| \left| \frac{30}{29.92} \right|} = 7.54$$

Solutions Chapter 13

13.31

Basis: 2m³ at 200 kPa and 25°C

$$p_{\text{CO}_2} = 200(0.8) = 160 \text{ kPa}$$

13.32

Basis: Gas at 30 psig and 20°C

Assume the barometric pressure = 14.7 psia

$$14.7 + 30.0 = 44.7 \text{ psia}$$

$$p_{\text{O}_2} = (44.7)(0.01) = 0.447 \text{ psia @ } 20^\circ\text{C}$$

13.33

Basis: 1 liter final volume

Assumptions:

- (1) Temperature is constant
- (2) Ideal gas law applies

$$p_T = p_{\text{O}_2} + p_{\text{N}_2} = (760 + 760) = 1,520 \text{ mm Hg}$$

Solutions Chapter 13

13.34

Basis: 1 lb mol of gas mixture

At 20°C

$$p_{\text{CO}_2} = p_T y_{\text{CO}_2} = 0.20(740) = 148 \text{ mm Hg}$$

$$p_{\text{O}_2} = p_T y_{\text{O}_2} = 0.60(740) = 444 \text{ mm Hg}$$

$$p_{\text{N}_2} = p_T y_{\text{N}_2} = 0.20(740) = 148 \text{ mm Hg}$$

At 40°C the pressure is

$$\frac{740 \text{ mm Hg}}{293 \text{ K}} \left| \frac{313 \text{ K}}{293 \text{ K}} \right| = 790.5 \text{ mm Hg}$$

$$(p_T) y_{\text{CO}_2} = p_{\text{CO}_2} = (0.20)(790.5) = \boxed{158.1 \text{ mm Hg}}$$

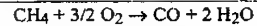
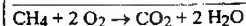
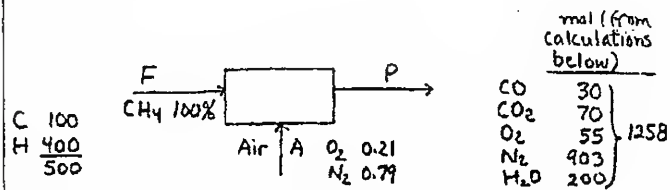
$$(p_T) y_{\text{O}_2} = p_{\text{O}_2} = (0.60)(790.5) = \boxed{474.3 \text{ mm Hg}}$$

$$(p_T) y_{\text{N}_2} = p_{\text{N}_2} = (0.20)(790.5) = \boxed{158.1 \text{ mm Hg}}$$

Solutions Chapter 13

13.35

Steps 1, 2, 3:



Step 4: Unknowns: P and all the compositions of P (5 unknowns)

Step 5: Balances: C, H, O, N + fact that 30% of C $\rightarrow$ CO

Step 6: Basis: 100 mol F

Steps 7, 8:

$$\begin{array}{l} \text{C balance: } 100 \text{ mol in CO} = 30 \text{ mol} \\ \text{CO}_2 = 70 \text{ mol} \\ \hline 100 \text{ mol} \end{array} \left. \vphantom{\begin{array}{l} 100 \text{ mol in CO} \\ \text{CO}_2 = 70 \text{ mol} \end{array}} \right\} \text{out}$$

$$\text{2N balance: Req'd. O}_2: 200 \text{ mol}$$

$$\text{XS O}_2: 0.20 (200) = 40$$

$$\text{Total O}_2 \text{ in } 240 \text{ mol}$$

(continued)

Solutions Chapter 13

$$\text{total } N_2 \text{ in} = \frac{240 \text{ O}_2}{0.21 \text{ O}_2} \left| \frac{0.79 \text{ N}_2}{0.21 \text{ O}_2} \right| = 903 \text{ mol} = n_{N_2, \text{out}}$$

$$2\text{H balance: mol H}_2\text{O out} = \text{mol H}_2 \text{ in} = \frac{400}{2} = 200 \text{ mol}$$

$$2\text{O balance: O}_2 \text{ in} - \text{O}_2 \text{ in CO, CO}_2, \text{H}_2\text{O} = \text{O}_2 \text{ out}$$

$$240 - \left(\frac{30}{2} + 70 + \frac{200}{2} \right) = 55 \text{ mol}$$

$$\text{alternate: XS O}_2 + \text{O}_2 \text{ not used for CO} = 40 + \frac{30}{2} = 55 \text{ mol}$$

$$p_{\text{CO}} = p_T y_{\text{CO}}$$

$$= (740) \left(\frac{30}{1258} \right)$$

$$= \boxed{17.7 \text{ mm Hg}}$$

13.36

a. F

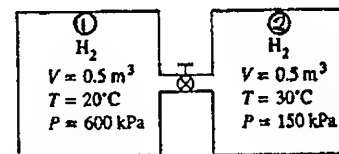
b. F

c. T

Solutions Chapter 13

13.37

Steps 2, 3, 4:



Step 5: Basis: Gas listed in the figure

Steps 6 and 7:

Unknowns p (final), V (final); Equations: ideal gas laws

$$V_{\text{final}} = 1 \text{ m}^3$$

$$n_1 + n_2 = n_{\text{final}}$$

Steps 8 and 9:

$$n_1 = \frac{p_1 V_1}{RT_1} \quad n_2 = \frac{p_2 V_2}{RT_2} \quad n_f = \frac{p_f V_f}{RT_f}$$

$$\frac{(600 \text{ kPa})(0.5 \text{ m}^3)}{293 \text{ K}} + \frac{(150 \text{ kPa})(0.5 \text{ m}^3)}{303 \text{ K}} = \frac{p_f (\text{kPa})(1.0 \text{ m}^3)}{288 \text{ K}}$$

$$p_{\text{final}} = \boxed{366 \text{ kPa}}$$

Solutions Chapter 13

13.38

Steps 2, 3, and 4: $p_1 = 55 + 14.7 = 69.7$ psia

Step 5: Basis: Gas with given data

Steps 6 and 7: Unknowns: T_1, T_2, T_f, p_f ($V_f = 400 + 50 = 450$ ft³)

Equations:

$$p_1 V_1 = n_1 RT_1 \quad T_1 = T_2 = T_f$$

$$p_2 V_2 = n_2 RT_2$$

$$n_1 + n_2 = n_f$$

$$p_f V_f = n_f RT_f$$

$$n_1 = \frac{p_1 V_1}{RT} = \frac{400(69.7)}{RT}$$

$$n_2 = \frac{(50)(14.7)}{RT}$$

$$p_f V_f = \left(\frac{50(14.7) + 400(69.7)}{RT} \right) RT$$

$$p_f = \frac{50(14.7) + 400(69.7)}{450} = \frac{28635}{450} = \boxed{63.8 \text{ psia}} = \boxed{48.9 \text{ psig}}$$

13.39

Steps 2, 3, and 4:

$$100 \text{ psig} = 114.7 \text{ psia} \quad \text{MW} = \frac{28 \text{ lb}}{1 \text{ lb mole}}$$

Solutions Chapter 13

$$60^\circ\text{F} = 520^\circ\text{R}$$

Step 5: Basis: 100 ft³ N₂ @ 100 psig and 60°F final moles

Final Moles:

$$\frac{100 \text{ ft}^3}{14.7 \text{ psia}} \left| \frac{114.7 \text{ psia}}{520^\circ\text{R}} \right| \left| \frac{1 \text{ lb mole}}{359 \text{ ft}^3} \right| = 2.056 \text{ lb mole}$$

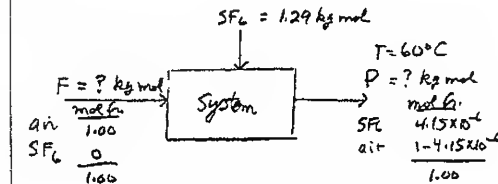
$$\text{Initial moles: } 2.056 + \frac{1}{28} = 2.092 \text{ lb mole}$$

$$\begin{aligned} \text{Initial pressure: } p &= \frac{nRT}{V} = \frac{2.092 \text{ lb mole} (80 + 460)^\circ\text{R}}{100 \text{ ft}^3} \left| \frac{0.7302(\text{ft}^3)(\text{atm})}{(\text{lb mole})(^\circ\text{R})} \right| \\ &= \boxed{8.24 \text{ atm abs.}} (121.2 \text{ psia}) \\ &\quad (106.5 \text{ psig}) \end{aligned}$$

13.40

Step 5: Basis: 1 min

Steps 2, 3, and 4:



(continued)

Solutions Chapter 13

$$\frac{28.8 \text{ m}^3 \text{ at SC}}{22.4 \text{ m}^3 \text{ at SC}} \times \frac{1 \text{ kg mol}}{1} = 1.29 \text{ kg mol}$$

Step 6: Unknowns: P, F

Step 7: Inddept. balances: air, SF₆

Steps 8-9: Balances are in moles

$$\text{SF}_6: F(0) + 1.29 = P(4.15 \times 10^{-6}) \text{ hence } P = 3.098 \times 10^5 \text{ kg mol}$$

$$\frac{3.098 \times 10^5 \text{ kg mol}}{1 \text{ kg mol}} \times \frac{22.4 \text{ m}^3 \text{ at SC}}{273} = \frac{60 + 273}{273} = 8.46 \times 10^6 \text{ m}^3/\text{min}$$

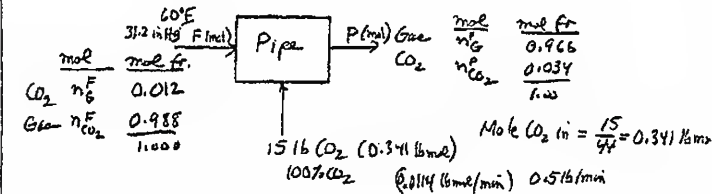
Alternate solution:

$$\frac{28.8 \text{ m}^3 \text{ at SC}}{273 \text{ K}} \times \frac{1}{4.15 \times 10^6} = 8.46 \times 10^6$$

13.41

Step 5: Basis: 15 lb CO₂ added = 30 min

Steps 2, 3, and 4:



Solutions Chapter 13

Step 6: Unknowns: F, P

Step 7: Balances: Gas, CO₂

Steps 8 and 9: Balance overall on process in moles

$$\text{Gas: } 0.988 (F) = P(0.966)$$

$$\text{CO}_2: 0.012 (F) + 0.341 = P(0.034)$$

$$\text{Total: } F + 0.341 = P$$

$$F = 14.79 \text{ lb mol} \quad P = 15.13 \text{ lb mol}$$

$$F = \frac{14.79 \text{ lb mol}}{30 \text{ min}} \times \frac{21.9 (\text{in Hg}) (\text{ft}^3)}{31.2 \text{ in Hg}} \times \frac{(60 + 460)^\circ \text{R}}{(\text{lb mol}) (^\circ \text{R})} = 182 \text{ ft}^3/\text{min}$$

at 60°F and 31.2 in Hg

13.42

The gas in the cell is composed partly of NO and partly of NO₂. We can use the ideal gas law to calculate the total gram moles present in the cell.

Basis: 100 cm³ of gas at 170 kPa and 30°C

$$R = \frac{101.3 \text{ kPa}}{273 \text{ K}} \left| \frac{22.41 \text{ L}}{1 \text{ g mol}} \right| \frac{1000 \text{ cm}^3}{1 \text{ L}} = 8.316 \times 10^3 \frac{(\text{kPa})(\text{cm}^3)}{(\text{K})(\text{g mol})}$$

$$n = \frac{pV}{RT} = \frac{170 \text{ kPa}}{8.316 \times 10^3 \frac{(\text{kPa})(\text{cm}^3)}{(\text{K})(\text{g mol})}} \left| \frac{100 \text{ cm}^3}{303 \text{ K}} \right| = 0.00675 \text{ g mol}$$

If the mixture is composed of NO (MW = 30) and NO₂ (MW = 46), because we know the total mass in the cell we can compute the fraction of, say, NO. Let x = grams of NO; then $(0.291 - x)$ = g NO₂. In a table format the calculation is

Component	g	Mol. Wt.	g mol
NO	x	30	$\frac{x}{30}$
NO ₂	$0.291 - x$	46	$\frac{0.291 - x}{46}$
Total	0.291		0.00675

or

$$\frac{x}{30} + \frac{0.291 - x}{46} = 0.00675$$

$$0.0333x + (0.291 - x)(0.0217) = 0.00675$$

$$x = 0.0366 \text{ g}$$

The weight percent NO is

$$\frac{0.0366}{0.291} (100) = 12.5\%$$

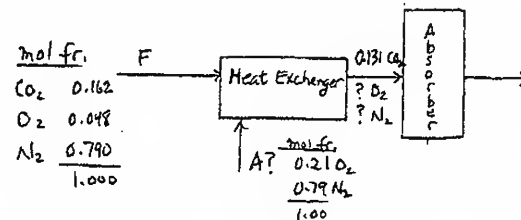
and the mole percent NO is

$$\frac{0.0366 \text{ g NO}}{0.00675 \text{ g mol total}} \left| \frac{1 \text{ g mol NO}}{30 \text{ g NO}} \right| (100) = 18\%$$

Can you let x be the mole fraction NO and obtain the same result? (Answer: Yes.)

13.43

Steps 2, 3, and 4:



Step 5: Basis: 2 min

Steps 6, 7, 8 and 9:

$$\text{mol of gas out} = \frac{30,000 \text{ ft}^3}{760 \text{ mm Hg}} \left| \frac{720 \text{ mm Hg}}{520^\circ \text{R}} \right| \left| \frac{492^\circ \text{R}}{359 \text{ ft}^3} \right| 1 \text{ mole} = 75 \text{ mol}$$

$$\frac{60 \text{ mol gas}}{1 \text{ mol gas}} \left| \frac{0.162 \text{ mol CO}_2}{1 \text{ mol gas}} \right| = 9.7 \text{ mol CO}_2 \text{ in}$$

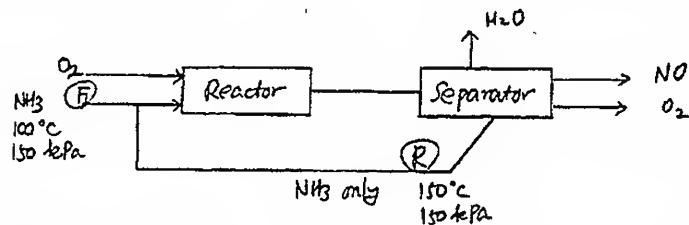
$$\frac{75 \text{ mol gas}}{1 \text{ mol gas}} \left| \frac{0.131 \text{ mol CO}_2}{1 \text{ mol gas}} \right| = 9.7 \text{ mol CO}_2 \text{ out}$$

$$\text{mol of gas in} = \frac{47,800 \text{ ft}^3}{760 \text{ mm Hg}} \left| \frac{740 \text{ mm Hg}}{1060^\circ \text{R}} \right| \left| \frac{492^\circ \text{R}}{359 \text{ ft}^3} \right| 1 \text{ mole} = 60 \text{ mol}$$

Thus since there are more moles out than in, one may assume the system does contain a leak. Also, assuming a leak would bring no additional CO₂ into the system, the above CO₂ balance calculations indicate the given analysis is probably correct.

Solutions Chapter 13

13.44

Basis: 1 mol of NH_3 fed

$$\text{NH}_3 \text{ balance: } (1 + R)(0.2) = R$$

$$0.8 R = 0.2$$

$$R = 0.25 \left(\frac{\text{mol NH}_3 \text{ recycled}}{\text{mol NH}_3 \text{ fed}} \right)$$

$$\frac{1 \text{ m}^3 (100^\circ\text{C}, 150 \text{ kPa}) \text{ NH}_3 \text{ fed}}{1 \text{ mol NH}_3 \text{ fed}} \left| \frac{0.25 \text{ mol recycled}}{(150 + 273)\text{K}} \right| \left| \frac{1 \text{ mol NH}_3 \text{ fed}}{(100 + 273)\text{K}} \right|$$

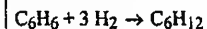
$$= 0.284 \left(\frac{\text{m}^3 \text{ recycled at } 150^\circ\text{C}, 150 \text{ kPa}}{\text{m}^3 \text{ NH}_3 \text{ fed at } 100^\circ\text{C}, 150 \text{ kPa}} \right)$$

13.45

Process: Steady state with reaction and recycle

Step 5: Basis: 1 min 260L C_6H_6

Solutions Chapter 13

Steps 2, 3, and 4: 950L H_2 Covert L $\rightarrow$ mol

$$\text{feed } n = \frac{pV}{RT}$$

$$p = 150 \text{ kPa}$$

$$n_{\text{H}_2} = 45.96 \text{ g mol}$$

$$T = 100^\circ\text{C} + 273 = 373\text{K}$$

$$n_{\text{C}_6\text{H}_6} = 12.58 \text{ g mol}$$

$$R = 8.314 \frac{(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}$$

Steps 6, 7, 8 and 9:

Select the overall system for the first balances.

	In	Out	+ generation	- Consumption	= 0
H_2 :	45.96	$n_{\text{H}_2}^\circ$	+	0	$- 0.75(45.96) = 0$
C_6H_6 :	12.58	$n_{\text{C}_6\text{H}_6}^\circ$	+	0	$- 0.75(45.96)\frac{1}{3} = 0$
C_6H_{12} :	0	$n_{\text{C}_6\text{H}_{12}}^\circ$	+	$0.75(45.96)\frac{1}{3}$	$- 0 = 0$

$$\text{from 1: } n_{\text{H}_2}^\circ = 11.5 \text{ g mol}$$

$$\text{from 2: } n_{\text{C}_6\text{H}_6}^\circ = 1.09 \text{ g mol}$$

$$\text{from 3: } n_{\text{C}_6\text{H}_{12}}^\circ = 11.5 \text{ g mol}$$

b. Volumetric flow rates: $T = 200^\circ\text{C} = 473\text{K}$
 $P = 100 \text{ kPa} = 0.987 \text{ atm}$

(continued)

Solutions Chapter 13

$$V_{n_1} = \frac{(n^{\circ}_{H_2})(RT)}{p} = 452 \text{ liters/min}$$

$$V_{C_2H_4} = 42.8 \text{ liters/min}$$

$$C_6H_{12} = 452 \text{ liters/min}$$

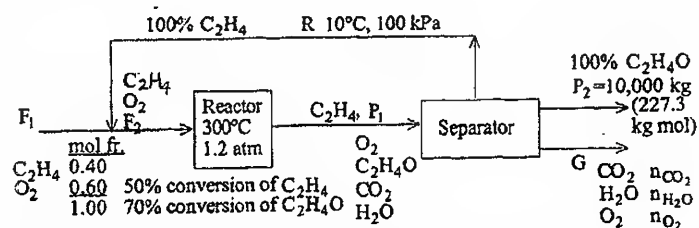
c. H_2 balance on Reactor + Separator

$$H_2: (45.95 + 0.90R) - (0.90R + 11.5) + 0 - 0.48(45.95 + 0.90R) = 0$$

Substitute for $n^{\circ}_{H_2}$ and solve to get $R = 28.7 \text{ kg mol}$

$$\text{Volumetric flow rate (R)} = \boxed{890 \text{ liters/min}}$$

13.46 Basis: 1 day = $10^4 \text{ kg C}_2\text{H}_2\text{O}$



If the overall system is chosen, the unknowns are F_1 and n_i , and three independent equations can be written from C, H, and O balances plus $n_{CO_2} = n_{H_2O}$.

Pick the system of the reactor plus separator, and use the data for the conversion.

Solutions Chapter 13

Step 5: Basis

$$\frac{10,000 \text{ kg}}{\text{day}} \left| \frac{1.00 \text{ kg mol}}{44 \text{ kg}} \right| = 227.3 \text{ kg mol } C_2H_4O/\text{day}$$

Steps 6, 7, 8 and 9:

Mixing point: $F_1 + R = F_2 \Rightarrow 0.40F_1 + R = n^F_{C_2H_4}$, $0.60F_1 = n^F_{O_2}$. Unknowns: $F_1, F_2, R, n^F_{O_2}, n^F_{C_2H_4}$

Reactor plus separator:

$$C_2H_4 \text{ balance: } \left[\begin{array}{c} \text{in} \\ 0.4(F_1) + R \end{array} \right] - \begin{array}{c} \text{out} \\ R \end{array} - \begin{array}{c} \text{consumed} \\ 0.4(F_1) + R \end{array} 0.5 = 0$$

$$C_2H_4O \text{ balance: } 0 - 227.3 + \begin{array}{c} \text{generation} \\ F_1(0.4) + R \end{array} (0.50)(0.70) = 0$$

$$F_1 = 811.79 \text{ kg mol/day}$$

$$R = 324.7 \text{ kg mol/day}$$

$$F_1 + R = F_2 = 1136.49$$

$$(a) \frac{1136.5 \text{ kg mol}}{\text{day}} \left| \frac{22.40 \text{ m}^3 \text{ at SC}}{1 \text{ kg mol}} \right| \left| \frac{1 \text{ day}}{24 \text{ hr}} \right| = \boxed{1059 \text{ m}^3 \text{ at SC/hr}}$$

$$(b) \frac{324.71 \text{ kg mol of } C_2H_4 \text{ in } R}{(811.79)(0.40) \text{ kg mol of } C_2H_4 \text{ in } F_1} \left| \frac{22.40 \text{ m}^3 \text{ at SC}}{273K} \right| \left| \frac{283K}{101.3 \text{ kPa}} \right| = \boxed{1.05}$$

Overall balances (kg mol): unknowns n_i ③

Balances ③

$$F_1$$

(continued)

Solutions Chapter 13

$$\text{C: } 811.79 (.40) (2) = 227.3 (2) + n_{\text{CO}_2} \quad n_{\text{CO}_2} = 194.83$$

$$\text{H: } 811.79 (.40) (4) = 227.3 (4) + n_{\text{W}} (2) n_{\text{W}} = 194.83$$

$$\text{O: } 811.79 (.60) (2) = 227.3 (1) + 194.83 (2)$$

$$+ 194.83 (1) + n_{\text{O}_2} (2) \quad n_{\text{O}_2} = 81.18$$

$$G = 194.83 + 194.83 + 81.18 = 470.84$$

$$\frac{470.84 \text{ kg mol P}_2}{\text{day}} \left| \frac{22.4 \text{ m}^3 \text{ at SC}}{\text{kg mol}} \right| \frac{353}{273} \frac{101.3}{100}$$

$$(c) = 1.38 \times 10^4 \text{ m}^3 \text{ gases/day at } 80^\circ\text{C and } 100 \text{ kPa}$$

13.47

Steps 2, 3 and 4:

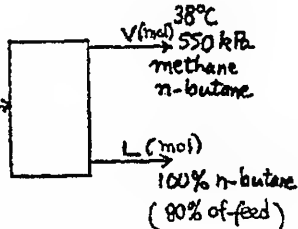
$$21^\circ\text{C} = 294\text{K}$$

$$3,000 \text{ m}^3/\text{day}$$

$$P_M = 103 \text{ kPa}$$

$$P_B = 586 \text{ kPa}$$

$$P_T = 689 \text{ kPa}$$



Step 5: Basis: 1 day

Solutions Chapter 13

Step 4:

mol in

$$pV = nRT$$

$$n = \frac{pV}{RT} = \frac{689 \text{ kPa} \left| \frac{3,000 \text{ m}^3}{8.314 (\text{kPa}) (\text{m}^3)} \right| \frac{(294 \text{ K})}{294 \text{ K}}} = 845.635 \text{ kg mol/day}$$

$$y = \frac{p}{P_T} \quad y_B = \frac{586 \text{ kPa}}{689 \text{ kPa}} = 0.8505 \frac{\text{mol C}_4\text{H}_{10}}{\text{mol feed}}$$

Steps 6-9:

mol C₄H₁₀ out

$$L = \frac{845.635 \text{ kg mol F}}{\text{day}} \left| \frac{0.8505 \text{ mol C}_4\text{H}_{10}}{\text{mol feed}} \right| \frac{0.8 \text{ mol C}_4\text{H}_{10}}{\text{mol C}_4\text{H}_{10} \text{ feed}} = 575.35 \frac{\text{mol C}_4\text{H}_{10}}{\text{day}}$$

overall mol balance (no reaction)

$$F = L + V$$

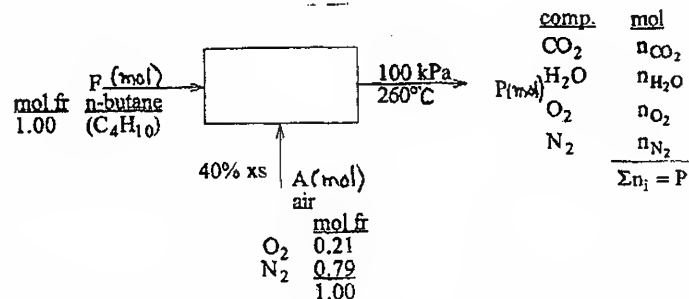
$$V = F - L = 845.635 - 575.35 = 270.26 \text{ kg mol}$$

$$pV = nRT$$

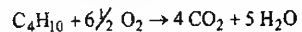
$$V = \frac{nRT}{p} = \frac{270.26 \text{ kg mol} \left| \frac{8.314 (\text{kPa}) (\text{m}^3)}{(270.26 \text{ kg mol}) (\text{K})} \right| \frac{311 \text{ K}}{550 \text{ kPa}}} = 1,270.57 \text{ m}^3$$

13.48

Steps 1, 2, 3, 4: Steady state problem with a reaction.



Step 5: Basis: 1 kg mol n-butane

Step 6: Unknowns are the moles in P (4) plus P .Step 7: The element balances are C, H, O, N, and we can use $\Sigma n_i = P$ so we can get a unique solution. You can use element balances or compound balances. The former is easier.Step 4: Calculate A given the 40.0% excess air.

$$\begin{array}{l} \text{In} \\ 1.00 \text{ kg mol } C_4H_{10} \left| \frac{6\frac{1}{2} \text{ kg mol } O_2}{1 \text{ kg mol } C_4H_{10}} \right. = 6.5 \text{ kg mol } O_2 \\ \\ 6.5(0.40) = 2.60 \text{ kg mol } O_2 \text{ xs} \\ = 9.10 \text{ kg mol } O_2 \text{ total} \end{array}$$

$$9.10 (0.79/0.21)$$

$$= 34.23 \text{ kg mol } N_2$$

Steps 7, 8, and 9:

Balances (kg mol)

	In	=	Out	
C:	1(4)	=	n_{CO_2}	$n_{CO_2} = 4$
H:	1(10)	=	$n_{H_2O}(2)$	$n_{H_2O} = 5$
O ₂ :	9.10	=	$n_{CO_2} + n_{O_2} + \frac{n_{H_2O}}{2}$	$n_{O_2} = 2.6$
N ₂	34.23	=	n_{N_2}	$n_{N_2} = 34.23$

$$P = 4 + 5 + 2.6 + 34.23 = 45.83 \text{ kg mol}$$

$$V = \frac{nRT}{p} = \frac{45.83 \text{ kg mol} \left| \frac{8.314 (\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})} \right| 533.1 \text{ K}}{100.0 \text{ kPa}} = 2.03 \times 10^3 \text{ m}^3$$

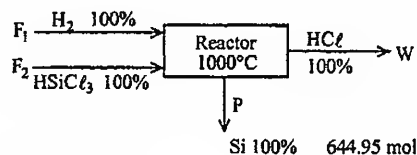
(continued)

Solutions Chapter 13

a.

flue gas analysis	kg mol	mol%
CO ₂	4	9
H ₂ O	5	11
O ₂	2.6	6
N ₂	34.23	75
Total	45.83	100

13.49



$$P = (D)(V) = D \left[\frac{\pi}{4} L (D_o^2 - D_i^2) \right] =$$

$$\frac{2.33 \text{ g}}{\text{cm}^3} \left| \frac{\pi}{4} \right| \left| \frac{100 \text{ cm}}{1} \right| \left| \frac{(10 \text{ cm})^2 - (1 \text{ cm})^2}{28.086 \text{ g}} \right| = 644.95 \text{ g mol Si product}$$

Si balance

$$\frac{F_2 \text{ g mol HSiCl}_3}{1 \text{ g mol HSiCl}_3} = P \text{ g mol Si, hence } F_2 = P$$

H g mol balance

$$\frac{F_1 \text{ g mol H}_2}{1 \text{ g mol H}_2} + \frac{2 \text{ g mol H}}{1 \text{ g mol H}_2} + \frac{F_2 \text{ g mol HSiCl}_3}{1 \text{ g mol HSiCl}_3} = \frac{W \text{ g mol HCl}}{1 \text{ g mol HCl}} + \frac{1 \text{ g mol H}}{1 \text{ g mol HCl}}$$

Solutions Chapter 13

Cl mol balance

$$F_1(0) + \frac{F_2 \text{ g mol HSiCl}_3}{1 \text{ g mol HSiCl}_3} \left| \frac{3 \text{ g mol Cl}}{1 \text{ g mol HSiCl}_3} \right| = \frac{W \text{ g mol HCl}}{1 \text{ g mol HCl}} \left| \frac{1 \text{ g mol Cl}}{1 \text{ g mol HCl}} \right|$$

Solution:

$$F_2 = P = 1 \text{ g mol HSiCl}_3$$

$$3F_2 = W = 3 \text{ g mol HCl}$$

$$2F_1 + F_2 = W$$

$$F_1 = \frac{3 \text{ g mol} - 1 \text{ g mol}}{2} = 1 \text{ g mol H}_2$$

$$\frac{1 \text{ g mol H}_2}{\text{g mol Si}} \left| \frac{644.95 \text{ g mol Si}}{1} \right| = 644.95 \text{ g mol H}_2$$

$$pV = nRT$$

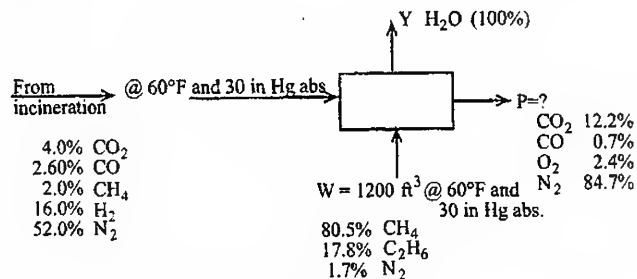
$$V = \frac{nRT}{p}$$

$$= \frac{644.95 \text{ g mol}}{(g \text{ mol})(K)} \left| \frac{82.06 (\text{cm}^3 \text{ atm})}{1 \text{ atm}} \right| \left| \frac{1273 \text{ K}}{1000 \text{ cm}^3} \right|$$

$$= \boxed{67,373 \text{ L}}$$

Solutions Chapter 13

13.50



Step 1, 2, 3, and 4: Steady state process with reaction.

Step 5: Basis: 1 min.

Step 6, 7, 8, 9:

Element balance: have C, H, O, N, and have 4 unknowns P, Y, F, A.

Basis: 1200 ft³ of W at 60°F and 20 in. Hg

	F_{in}	A_{in}	W_{in}	Y_{out}	P_{out}						
C:	$(0.04 + 0.26 + 0.02) F$	$+$	0	$+$	$(0.805 + 2 \times 0.178) W$	$-$	0	$-$	$(0.122 + 0.007) P$	$=$	0
N ₂ :	$(0.52) F$	$+$	$0.79 A$	$+$	$0.017 W$	$-$	0	$-$	$(0.847) P$	$=$	0
H ₂ :	$(0.04 + 0.16) F$	$+$	0	$+$	$(1.61 + 0.534) W$	$-$	Y	$-$	0	$=$	0
O:	$(0.08 + 0.26) F$	$+$	$0.42 A$	$+$	0	$-$	Y	$-$	$(0.244 + 0.007 + 0.048) P$	$=$	0

Introduce $W = 1200 \text{ ft}^3$

C:	$0.32 F$	$+$	0	$+$	1393.2 ft^3	$-$	0	$-$	$0.129 P$	$=$	0
N ₂ :	$0.52 F$	$+$	$0.79 A$	$+$	20.4 ft^3	$-$	0	$-$	$0.847 P$	$=$	0
H ₂ :	$0.20 F$	$+$	0	$+$	2572.8 ft^3	$-$	Y	$-$	0	$=$	0
O:	$0.34 F$	$+$	$0.42 A$	$+$	0	$-$	Y	$-$	$0.299 P$	$=$	0

Solutions Chapter 13

Solve: $F = 3,975 \text{ ft}^3$

$A = 19,510 \text{ ft}^3$

$Y = 3,370 \text{ ft}^3$

$P = 20,660 \text{ ft}^3$

$$\text{Air in} = \frac{19,510 \text{ ft}^3 @ 60^\circ\text{F} \text{ \& } 30 \text{ inches Hg}}{\frac{540^\circ\text{R}}{520^\circ\text{R}} \frac{30 \text{ inches Hg}}{29.6 \text{ inches Hg}}} = 20,535 \text{ ft}^3$$

13.51

Basis: 1 lb mol of 50% H₂ and 50% C₂H₆O

$$p_1 V_1 = n_1 R T_1 \quad p_2 V_2 = n_2 R T_2 \quad T_1 = T_2$$

$$\frac{p_1}{p_2} = \frac{n_1}{n_2} \quad \frac{760 \text{ mm Hg}}{700 \text{ mm Hg}} = \frac{1}{n_2} \text{ hence } n_2 = 0.922 \text{ lb mol}$$

Let $y = \text{mol of C}_2\text{H}_6\text{O formed}$

$$(0.5 - y) + (0.5 - y) + y = 0.922$$

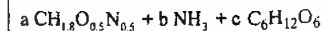
from which $y = 0.079 \text{ lb mol C}_2\text{H}_6\text{O formed}$

$$\text{Degree of completion} = \frac{0.079}{0.50} \times 100 = 15.8\%$$

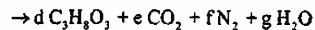
13.52

C₆H₁₂O₆ is glucose and C₃H₈O₃ is glycerol

The reaction equation is



(continued)



The amount of CO_2 measured (52.4 L at 95 kPa and 300 K) is

$$\frac{52.4 \text{ L CO}_2}{1000 \text{ L}} \left| \frac{1 \text{ m}^3}{95 \text{ kPa}} \right| \left| \frac{1}{300 \text{ K}} \right| \left| \frac{(\text{kg mol})(\text{K})}{8.314 (\text{kPa})(\text{m}^3)} \right| = 2 \times 10^{-3} \text{ kg mol or } 2.00 \text{ g mol}$$

Use element balances and specifications to get the coefficients in the reaction equation. Let $c = 1$ (divide both sides by c) be the basis for obtaining the coefficients: then there are 6 unknowns, 4 equations, and two specifications:

$$\text{C: } a + 6c = 3d + e$$

$$\text{H: } 1.8a + 3b + 12 = 8d + 2g$$

$$\text{O: } 0.5a + 6 = 3d + 2.00(2) + g$$

$$\text{N: } 0.5a + b = 2b$$

Specifications:

$$\frac{f}{b} = 1 \quad \text{and} \quad \frac{e}{c} = 2$$

The solution of the equations is:

$$a = 7.27, \quad b = 3.64, \quad d = 1.09, \quad f = 3.64, \quad g = 1.64$$

The glycerol produced was $\boxed{1.09 \text{ g mol}}$, and

The biomass reacted was $\boxed{7.27 \text{ g mol}}$

13.53

Basis: 1 hr

$$\text{a. } \frac{2.5 \times 10^{-3} \text{ g mol O}_2}{(10^3 \text{ cells})(\text{hr})} \left| \frac{2.9 \times 10^6 \text{ cells}}{\text{mL}} \right| \left| \frac{10^3 \text{ mL}}{1 \text{ g mol}} \right| \left| \frac{10^3 \text{ mg mol}}{\text{hr}} \right| = \boxed{725 \text{ mg mol/hr}}$$

$$\text{b. } \frac{45 \text{ L gas}}{\text{h}} \left| \frac{0.40 \text{ L O}_2}{1 \text{ L gas}} \right| \left| \frac{110 \text{ kPa}}{10^3 \text{ L}} \right| \left| \frac{1 \text{ m}^3}{298 \text{ K}} \right| \left| \frac{(\text{kg mol})(\text{K})}{8.314 (\text{kPa})(\text{m}^3)} \right|$$

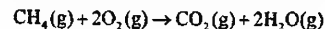
$$= 7.99 \times 10^{-4} \text{ kg mol/hr} \quad \text{or} \quad \boxed{799 \text{ mg mol/hr}}$$

c. $\boxed{\text{Increase}}$

13.54

Basis: 10^6 m^3 at SC of CH_4 burned completely

Ignore the oxidation of S, N, and C going to CO in the material balance to simplify the calculations. Including those products will have negligible effect on the N_2 and CO_2 produced.



Calculate the kg mol of CH_4 burned:

$$\frac{10^6 \text{ m}^3 \text{ at SC}}{22.415 \text{ m}^3} \left| \frac{\text{kg mol}}{1} \right| = 44,613 \text{ kg mol}$$

Assume 10% excess air is used. Base the CO_2 on the emission factor value.

	$\frac{\text{kg mol}}{(\text{kg mol}) \text{ Emission factor}}$
Required O_2 entering: $44,613(2) =$	89,226
Excess O_2 (0.1)(89,226)	8,923
Total O_2 :	98,149
N_2 entering: $98,149(79/21) =$	369,227

(continued)

Solutions Chapter 13

<u>Exit gas</u>				
CO ₂ produced:	44,613	→	43,812	0.086
N ₂ exiting:	369,227	→		0.722
H ₂ O exiting: (2)(44,613) =	89,226	→		0.174
O ₂ exiting: (0.10)(89,226) =	8,923	→		0.017
SO ₂ : (9.6)/64 =			0.15	2.9×10^{-7}
NO ₂ : { 3040/46 =			66	1.3×10^{-7}
1600/46 =			35	6.8×10^{-5}
1500/46 =			33	6.4×10^{-5}
CO { 1344/28 =			48	9.3×10^{-5}
640/28 =			23	4.5×10^{-5}
Total (about)			511,200	1.00

On a dry basis:

	<u>mol ft.</u>
SO ₂	3.5×10^{-7}
NO ₂	1.6×10^{-4} , 8.2×10^{-5} , and 7.8×10^{-5} respectively
CO	1.1×10^{-4} and 5.5×10^{-5} , respectively

13.55

Basis: 10³ L of No. 6 fuel oil

$$\frac{10^3 \text{ L oil}}{1 \text{ cm}^3} \left| \frac{0.86 \text{ g}}{1 \text{ cm}^3} \right| \frac{1000 \text{ cm}^3}{1 \text{ L}} = 8.6 \times 10^5 \text{ g or } 8.6 \times 10^2 \text{ kg of oil}$$

To get the moles of pollution components alone in the gas produced, the kg have to be converted using MW (ignore the particulate matter)

Solutions Chapter 13

	<u>kg</u>	<u>MW</u>	<u>g mol</u>	<u>m³ at SC on the basis of 10³/kg</u>
SO ₂	19 (0.84) = 15.96	64	249	6.5
SO ₃	0.69 (0.84) = 0.580	80	7.3	0.18
NO ₂	8	46	174	4.5
CO	0.6	28	21	0.55
CO ₂	3025	44	6.875×10^4	1,790

Example of calculating the m³ at SC on the basis of 1 metric ton (10³ kg) of No. 6 fuel oil burned:

$$\text{SO}_2: \frac{0.249 \text{ kg mol}}{8.6 \times 10^2 \text{ kg oil}} \left| \frac{22.415 \text{ m}^3 \text{ at SC}}{1 \text{ kg mol}} \right| \frac{10^3 \text{ kg oil}}{1} = \boxed{6.5 \text{ m}^3 \text{ at SC}}$$

13.56

Basis: 10³ L of No. 6 fuel oil

$$\frac{10^3 \text{ L oil}}{1 \text{ cm}^3} \left| \frac{0.86 \text{ g}}{1 \text{ cm}^3} \right| \frac{1000 \text{ cm}^3}{1 \text{ L}} = 8.6 \times 10^5 \text{ g or } 8.6 \times 10^2 \text{ kg oil}$$

Calculate the kg mol of each compound in the oil:

	<u>Mass fraction</u>	<u>kg</u>	<u>MW</u>	<u>kg mol</u>
C	0.8726	750.4	12	62.53
H	0.1049	90.21	1.008	89.49
O	0.64×10^{-2}	5.5	16	0.34
N	0.28×10^{-2}	2.4	14	0.17
S	0.84×10^{-2}	7.2	32	0.23
ash	0.04×10^{-2}	0.3	-	-

Calculate the moles of product gas

(continued)

Solutions Chapter 13

CO ₂ :	C + O ₂ → CO ₂	<u>kg mol</u> 62.53	<u>MW</u> 44	<u>kg</u> 2751
N:	N + O ₂ → NO ₂	0.17	46	7.8
S:	The SO ₂ and SO ₃ are from the EPA data and Problem 13.55			
	SO ₃ :	<u>kg</u> 0.58	<u>kg mol</u> 0.0073	
	SO ₂	15.96	0.249	

If the S + O₂ → SO₂ is used as the product from the S in the oil, the value of 0.23 can be compared with 0.25 (ignoring the SO₃).

Solutions Chapter 14

14.1

Basis: 7 lb N₂ or 7/28 = 0.25 lb mol N₂

$$a. \quad p = \frac{nRT}{V} = \frac{0.25 \text{ lb mol}}{0.75 \text{ ft}^3} \left| \frac{(120 + 460)^\circ \text{R}}{(\text{lb mol})(^\circ \text{R})} \right| \frac{0.732(\text{atm})(\text{ft}^3)}{(\text{lb mol})(^\circ \text{R})} = 141 \text{ atm}$$

$$b. \quad T_c = 126.3 \text{ K} \quad p_c = 33.54 \text{ atm} \quad T_r = \frac{580}{(126.3)(1.8)} = 2.55$$

$$V_r' = \frac{\hat{V}}{\frac{RT_c}{p_c}} = \frac{\frac{0.75 \text{ ft}^3}{0.25 \text{ lb mol}}}{(1.314) \frac{(\text{atm})(\text{ft}^3)}{(\text{lb mol})(\text{K})} (126.3 \text{ K})} = 0.607$$

From the compressibility charts

$$p_r = 4.3 \quad \text{so that} \quad p = p_r p_c = (4.3)(33.54) = 144 \text{ atm}$$

Note: You calculate z from T_r and V_r' , and then use $p = \frac{znRT}{V}$

14.2

Basis: 2 g mol C₂H₄

$$p_c = 50.5 \text{ atm} \quad T_c = 283.1 \text{ K}; p = ? \quad T = 95 + 273.1 = 368.1 \text{ K}$$

$$\hat{V}_{c_i} = \frac{RT_c}{p_c} = \frac{82.06(\text{cm}^3)(\text{atm})}{(\text{g mol})(\text{K})} \left| \frac{283.1 \text{ K}}{50.5 \text{ atm}} \right| = 460 \text{ cm}^3/\text{g mol}$$

Solutions Chapter 14

$$\hat{V} = \frac{418 \text{ cm}^3}{2} = 209 \text{ cm}^3/\text{g mol}$$

$$\frac{\hat{V}}{\hat{V}_{c_i}} = \hat{V}_r = 0.45 \quad T_r = \frac{368.1}{283.1} = 1.30$$

From chart, $p_r = 2$, hence $p = 101 \text{ atm}$.

Use of the Pitzer acentric factor would require a trial and error solution.

14.3

Basis: 3 lb mol of gas at 252°C and 463 psia.

Volume = 50 ft³

$$R = \frac{(1 \text{ atm})(359 \text{ ft}^3)}{(1 \text{ lb mol})(273 \text{ K})} = 1.315 \frac{(\text{atm})(\text{ft}^3)}{(\text{lb mol})(\text{K})}$$

$$z = \frac{\left(\frac{463 \text{ psia}}{14.7 \frac{\text{psia}}{\text{atm}}} \right) (50 \text{ ft}^3)}{(3 \text{ lb mol}) \left(1.315 \frac{(\text{atm})(\text{ft}^3)}{(\text{lb mol})(\text{K})} \right) (273 + 252^\circ \text{C})} = 0.76$$

The Pitzer acentric factor is not as convenient to use as the compressibility charts.

From compressibility charts (see the CD for better precision)

$$z = 0.76 \quad T_r = \frac{525}{500} = 1.05$$

$$p_r = 0.7$$

(continued)

Solutions Chapter 14

Thus

$$\frac{463 \text{ psia}}{p_c} = 0.7$$

$$p_c = \boxed{661 \text{ psia}} (45.0 \text{ atm})$$

14.4

Basis: 1 lb n-octane

$$T_c = 1025^\circ\text{R} \quad p_c = 24.6 \text{ atm} \quad \text{MW} = 114$$

$$p_r = \frac{27}{24.6} = 1.10$$

To get the temperature of the gas

$$\frac{1 \text{ lb}}{114 \text{ lb}} \left| \frac{1 \text{ lb mol}}{359 \text{ ft}^3 \text{ SC}} \right| \left| \frac{1 \text{ atm}}{27 \text{ atm}} \right| \left| \frac{T \text{ K}}{273 \text{ K}} \right| z = 0.20 \text{ ft}^3$$

$$T_z = 845 \quad zT_R = 845/1025 = 0.825$$

From the compressibility Chart Fig. 14.4b (expanded in the CD)

$$\text{read } T_r = 1.16, \text{ so that } T = (1.16)(1025) = \boxed{1189^\circ\text{R}} (729^\circ\text{F})$$

Alternate solution: Calculate $z = 0.71$ and use $pV = znRT$.

Solutions Chapter 14

14.5

Basis: 50 lb CO₂ (50/44) = 1.138 lb mol CO₂

$$V = 5.0 \text{ ft}^3 \quad p = 1600 + 14.7 = 1614.7 \text{ psia}$$

$$P_c = 1070 \text{ psia} \quad T_c = 547.5^\circ\text{R}$$

$$p_r = \frac{1614.7}{1070} = 1.51 \quad \hat{V} = \frac{5.0}{1.138} = 4.40 \text{ ft}^3/\text{lb mol}$$

$$V_d = 5.50 \text{ ft}^3/\text{lb mol} \quad \text{so that } V_n = \frac{4.40}{5.50} = 0.800$$

T_r from Figure 14.4b is (expanded in the CD) is 1.44

$$T = (1.44) (547.5) = \boxed{788^\circ\text{R}} (328^\circ\text{F})$$

The Pitzer acentric factor is less convenient to use for this problem.

14.6

Basis: 10 kg CH₄

$$\text{MW CH}_4 = 16.03 \quad \frac{10 \text{ kg}}{16.03 \text{ kg}} \left| \frac{1 \text{ kg mol}}{16.03 \text{ kg}} \right| = 0.624 \text{ kg mol}$$

$$T_c = 305.4 \text{ K and } p_c = 4883 \text{ kPa}$$

$$V = 0.0250 \text{ m}^3 \quad p = 14,000 \text{ kPa gauge} = 14,015 \text{ kPa absolute}$$

$$p_r = \frac{14,015}{4883} = 2.87$$

(continued)

Solutions Chapter 14

$$\hat{V}_{ci} = \frac{RT_c}{p_c} = \frac{(8.314)(305.4)}{4883} = 0.520 \text{ m}^3/\text{kg mol}$$

$$V_r = \frac{0.0250}{0.520} = 0.048$$

From the compressibility chart, $T_r \cong 1.05$ hence $T = (1.05)(305.4) = \boxed{321 \text{ K}}$

14.7

Basis: 1 ft³ CH₄

$$pV = nRTz \quad p = 214.7 \text{ psia}$$

$$R = \frac{10.73(\text{psia})(\text{ft}^3)}{(\text{lb mol})(^\circ\text{R})}$$

$$T_c = 191^\circ\text{K} \rightarrow 344^\circ\text{R} \quad p_c = 45.79 \text{ atm} \rightarrow 672.9 \text{ psia}$$

$$T_r = 540/344 = 1.57 \quad p_r = \frac{214.3}{672.9} = 1.0$$

$$z = 0.975$$

$$n = \frac{(214.3)(1)}{(10.73)(540)(0.975)} = 0.038 \text{ lb mol}$$

$$\text{weight (mass)} = (0.038)(16.03) = \boxed{0.608 \text{ lb}}$$

By use of the Pitzer acentric factor ($\omega = 0.008$ for CH₄)

$$z = z^0 + z^1\omega = 0.976 + 0.024(0.008) = 0.976$$

Solutions Chapter 14

14.8

Basis: 25L of CO₂ at 25°C and 200 kPa

$$\text{For CO}_2: \quad p_c = 7385 \text{ kPa}$$

$$T_c = 304.2 \text{ K}$$

$$p_r = \frac{p}{p_c} = \frac{200 \text{ kPa}}{7385 \text{ kPa}} = 0.0271$$

$$T_r = \frac{T}{T_c} = \frac{(25 + 273) \text{ K}}{304.2^\circ \text{ K}} = 0.98$$

From the compressibility chart, at these coordinates, $z \cong 0.99$

$$pV = nRTz$$

$$n = \frac{200 \text{ kPa}}{101.3 \text{ kPa}} \left| \frac{1 \text{ atm}}{101.3 \text{ kPa}} \right| \frac{25 \text{ L}}{0.08206(\text{L})(\text{atm})} \left| \frac{(\text{g mol})(\text{K})}{298 \text{ K}} \right| \frac{1}{0.99}$$

$$= 2.04 \text{ g mol}$$

$$m = (2.04)(44) = 87.9 \text{ g} \quad \text{or} \quad \boxed{0.0879 \text{ kg}}$$

14.9

Basis: 106 ft³ at 60°F and 14.7 psia

$$p_r V_r = z_r n_r R_r T_r \quad \text{at the reservoir}$$

$$pV = znRT \quad \text{at SC}$$

$$T_r = \frac{T}{T_c} = \frac{120 + 460}{191(1.8)} = \frac{580}{344} = 1.69$$

(continued)

Solutions Chapter 14

$$p_r = \frac{p}{p_c} = \frac{1000}{(45.79)(14.7)} = \frac{1000}{674} = 1.48$$

$$z_r = 0.95$$

$$V_i = V \left(\frac{p}{p_r} \right) \left(\frac{T_r}{T} \right) \left(\frac{z_r}{z} \right) = 10^6 \left(\frac{14.7}{1000} \right) \left(\frac{120 + 460}{60 + 460} \right) \left(\frac{0.95}{1} \right) = \boxed{15,600 \text{ ft}^3}$$

14.10

Basis: 1 kg propane

For propane: $T_c = 370 \text{ K}$ $p_c = 4255 \text{ kPa}$

$$\text{and } \bar{R} = 0.18855 \text{ (kJPa)(m}^3\text{)/(kg)(K)}$$

$$\text{Reduced temperature} = T_r = \frac{T}{T_c} = \frac{230 + 273.2}{370} = 1.36$$

$$\text{Reduced pressure} = p_r = \frac{p}{p_c} = \frac{6000}{4255} = 1.408$$

From a generalized compressibility chart

at $p_r = 1.408$ and $T_r = 1.36$, $z \approx 0.80$

$$\text{Since } pV = znRT, \quad \hat{V} = \frac{zRT}{p}$$

$$\hat{V} = \frac{(0.80)(0.18855)(503.2)}{(6000)} = \boxed{0.0127 \text{ m}^3/\text{kg}}$$

Solutions Chapter 14

14.11

- | | | | |
|----|-----|----|----|
| a) | Yes | g) | No |
| b) | No | h) | No |
| c) | Yes | | |
| d) | No | | |
| e) | Yes | | |
| f) | No | | |

14.12

Basis: 1 g mol $\text{C}_6\text{H}_5\text{Cl}$ (MW = 112.56)

$$p_c = 4518 \text{ kPa} \quad T_c = 632.4 \text{ K}$$

$$p_r = \frac{230}{4518} = 0.051 \quad T_r = \frac{380}{632.4} = 0.601$$

These values fall below the gaseous region in the compressibility chart here $\text{C}_6\text{H}_5\text{Cl}$ is not a gas. It is a liquid (sp.gr = 1.107), so that the volume is $(1)(112.56)/1.107 =$

$$\boxed{102 \text{ cm}^3}$$

14.13

Basis: Data on gases cited in problem.

- a. The cubic feet associated with "165 ft³" and "240 ft³" probably means that the values are the respective volumes of an ideal gas at standard conditions, because the volumes calculated for the gases in part b. below are quite different than the stated values.

(continued)

Solutions Chapter 14

b. To find the amount of gas in the cylinder, first find the approximate volume in the cylinder.

$$V_{\text{cyl}} = \frac{\pi d^2 h}{4} = \frac{(3.14)(9)^2(52)}{(4)(1728)} = 1.914 \text{ ft}^3$$

Use the gas law as ratios:

$$\frac{p_2 V_2}{p_1 V_1} = \frac{z_2 R T_2}{z_1 R T_1}$$

$$V_2 = V_1 \left(\frac{p_1}{p_2} \right) \left(\frac{z_2 T_2}{z_1 T_1} \right)$$

For C_2H_4 :

$$T_c = 283 \text{ K}, p_c = 50.5 \text{ atm}$$

$$\text{Assume } T_1 = 80^\circ\text{F} = 540^\circ\text{R} = 300^\circ\text{K}$$

$$\left. \begin{aligned} T_1 &= \frac{300}{283} = 1.06 \\ p_1 &= \frac{1515}{(14.7)(50.5)} = 2.05 \end{aligned} \right\} z_1 = 0.35$$

(At standard conditions: $z_2 = 1.00$)

$$V_2 = (1.914) \left(\frac{1515}{14.7} \right) \left(\frac{1}{0.35} \right) \left(\frac{492}{540} \right) = 514 \text{ ft}^3$$

For CH_4 :

$$T_c = 191 \text{ K}, p_c = 45.8 \text{ atm}$$

$$T_1 = \frac{300}{191} = 1.57 \quad p_1 = \frac{2015}{(14.7)(45.8)} = 2.98$$

Solutions Chapter 14

$$z_2 = 0.84$$

$$V_2 = (1914) \left(\frac{2015}{14.7} \right) \left(\frac{1}{0.84} \right) \left(\frac{492}{540} \right) = 285 \text{ ft}^3$$

$$\text{MW of } \text{C}_2\text{H}_4 = 28$$

$$\text{MW of } \text{CH}_4 = 16$$

$$\text{wt of } \text{C}_2\text{H}_4 = \frac{(514)}{(359)} \left| \frac{28}{1} \right| = 40.1$$

$$\text{wt of } \text{CH}_4 = \frac{(285)}{(359)} \left| \frac{16}{1} \right| = 12.7$$

$$\text{Therefore } \text{wt}_{\text{C}_2\text{H}_4} > \text{wt}_{\text{CH}_4}$$

c. For C_2H_4 :

$$pV = znRT = z \frac{m}{\text{MW}} RT$$

$$m = \frac{pV(\text{MW})}{zRT} = \frac{(1515)(1.91)(28)}{(0.35)(10.73)(590)} = 40 \text{ lb } \text{C}_2\text{H}_4$$

For CH_4 :

$$m = \frac{(2015)(1.91)(16)}{(0.84)(10.73)(540)} = 12.7 \text{ lb } \text{CH}_4$$

Check with cylinder:

$$163 - 90 = 123 \text{ lb cylinder}$$

$$105 - 9.5 = 135 \text{ lb cylinder}$$

Solutions Chapter 14

14.14

The answer is it depends on the gas temperature and the pressure. If $pV = znRT$ applies, the ideal gas law is represented by $z = 1$, and for a non-ideal gas, z can be greater or less than 1. The pressure is $p = \frac{znRT}{V}$. So $p_{\text{real}} = p_{\text{ideal}} z$, for fixed V and for a fixed number of moles and temperature (the volume of cylinder is fixed). The pressure prediction by the ideal gas law will be conservative (higher than the true pressure) for $z < 1$, and lower than the true pressure for $z > 1$.

14.15

$$a) \quad p_1 V_1 = z_1 n_1 RT \quad R = \text{constant}$$

$$p_2 V_1 = z_2 n_2 RT_1 \quad V_1 = \text{constant, the vol. of cylinder}$$

$$\frac{p_1}{p_2} = \frac{z_1 n_1}{z_2 n_2} \quad T_c = 133.0 \text{ K}$$

$$T_r = \frac{T}{T_c} = \frac{24.44 + 273}{133} = 2.24 \quad p_c = 34.5 \text{ atm}$$

$$p_h = \frac{2000 \text{ psig} + 14.7}{14.7 \text{ psig/atm}} \left| \frac{1}{34.5 \text{ atm}} \right| = 3.97$$

$$p_{r_2} = 3.80$$

$$\left. \begin{array}{l} z_1 = 1.0 \\ z_2 = 1.0 \end{array} \right\} \text{Ideal gas behavior}$$

$$\frac{p_1}{p_2} = \left(\frac{n_1}{n_2} \right) \left(\frac{1.0}{1.0} \right) = \frac{n_1}{n_2}$$

Solutions Chapter 14

$$n_{\text{CO}} = \frac{pV}{RT} = \frac{14.7 \text{ psia}}{536^\circ\text{R}} \left| \frac{175 \text{ ft}^3}{10.73 \frac{(\text{psia})(\text{ft}^3)}{(\text{lb mol})(^\circ\text{R})}} \right| = 0.447 \text{ lb mol}$$

$$V_{\text{cylinder}} = \frac{n_{\text{CO}} RT_1}{p_1}$$

$$V_c = \frac{0.447 \text{ lb mol}}{2014.7 \text{ psia}} \left| \frac{10.73 (\text{psia})(\text{ft}^3)}{(\text{lb mol})(^\circ\text{R})} \right| \frac{536^\circ\text{R}}{1} = 1.276 \text{ ft}^3$$

$$n_{\text{final, CO}} = \frac{p_2 V_c}{RT} = \frac{1924.7 \text{ psia}}{10.73 \frac{(\text{psia})(\text{ft}^3)}{(\text{lb mol})(^\circ\text{R})}} \left| \frac{1.276 \text{ ft}^3}{536^\circ\text{R}} \right| = 0.427 \text{ lb mol}$$

$$n_{\text{CO, lost}} = (0.447 - 0.427) \text{ lb mol} \approx 0.020 \text{ lb mol}$$

$$\text{rate of loss} = \frac{0.020 \text{ lb mol}}{48 \text{ hr}} \left| \frac{1}{1} \right| = 4.167 \times 10^{-4} \frac{\text{lb mol}}{\text{hr}}$$

$$b) \quad n_{\text{air}} = \frac{pV}{RT} = \frac{14.7 \text{ psia}}{536.0^\circ\text{R}} \left| \frac{1600 \text{ ft}^3}{10.73 \frac{(\text{psia})(\text{ft}^3)}{(\text{lb mol})(^\circ\text{R})}} \right| = 4.09 \text{ lb mol air}$$

$$100 \text{ ppm} = 100 (10^{-6}) (4.09 \text{ lb mol}) = 4.09 \times 10^{-4} \text{ lb mol}$$

$$t = \frac{4.09 \times 10^{-4}}{4.167 \times 10^{-4} \frac{\text{lb mol}}{\text{hr}}} = 0.982 \text{ hr}$$

(continued)

Solutions Chapter 14

$$c) \quad t = 67 \text{ hr} \quad n_{\text{CO}} = \frac{4.167 \times 10^4}{67} = 0.0279 \text{ lb mol}$$

$$C_{\text{CO}} = \frac{0.0279 \text{ lb mol}}{1600 \text{ ft}^3} = \boxed{1.75 \times 10^{-5} \frac{\text{lb mol}}{\text{ft}^3}}$$

d) The CO alarms would go on to alert people in the building.

14.16

a) The density of the gas must be 2.0 g/m^3 . MW is Si is 28.086 so
 $\hat{V} = (2/28.086) = 0.0712 \text{ g mol/cm}^3$. Let $T = 298 \text{ K}$. Also $z = 1$ at $T_r = 1.98$
 and V_{r1} very large.

$$p = \frac{zRT}{\hat{V}} = \frac{1}{0.0712} \left[\frac{8.314 (\text{Pa})(\text{m}^3)}{(\text{g mol})(\text{K})} \right] \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^3 \left| \frac{298 \text{ K}}{1} \right| = 2.48 \times 10^9 \text{ Pa}$$

b) For a lower pressure, use a less dense gas (lower MW).

c) At too high a temperature, you cannot get adequate density.

14.17

Basis: 240 ft^3 methane at 80°F and 1964.7 psia . Assume the number of moles does not change.

$$\frac{p_1 V_1}{p_2 V_2} = \frac{n R T_1 z_1}{n R T_2 z_2}$$

Solutions Chapter 14

$$\frac{p_1}{p_2} = \frac{T_1 z_1}{T_2 z_2}$$

$$T_2 = \frac{T_1 z_1 p_2}{z_2 p_1}$$

Calculation of z_1

Methane $\Rightarrow T_c = 190.7 \text{ K} \quad p_c = 45.8 \text{ atm}$

$$T_1 = 80^\circ\text{F} \Rightarrow 299.82 \text{ K}$$

$$T_{r1} = \frac{299.82 \text{ K}}{190.7 \text{ K}} = 1.572$$

$$p_{r1} = \frac{133.7 \text{ atm}}{45.8 \text{ atm}} = 2.919$$

$$\therefore z_1 = 0.83$$

Calculation of z_2

$$p_1 = (1950 \text{ psig} + 14.7 \text{ psia}) \left(\frac{1 \text{ atm}}{14.7 \text{ psia}} \right) = 133.7 \text{ atm}$$

$$p_2 = (3000 \text{ psig} + 14.7 \text{ psia}) \left(\frac{1 \text{ atm}}{14.7 \text{ psia}} \right) = 205.08 \text{ atm}$$

$$p_r = \frac{205.08 \text{ atm}}{45.8 \text{ atm}} = 4.478$$

$$V = 240 \text{ ft}^3 \left(2.832 \times 10^{-2} \text{ m}^3 / 1 \text{ ft}^3 \right) \left(100 \text{ cm}^3 / 1 \text{ m}^3 \right)$$

$$= 6.797 \times 10^6 \text{ cm}^3$$

(continued)

Solutions Chapter 14

$$\hat{V}_{c1} = \frac{RT_c}{p_c} = \frac{82.06(\text{cm}^3\text{atm})/(\text{g mol})(\text{K}) (190.7\text{K})}{45.8 \text{ atm}}$$

$$= 341.68 \frac{\text{cm}^3}{\text{g mol}}$$

$$n = \frac{p_1 V_1}{z_1 R T_1} = \frac{(45.8 \text{ atm})(6.797 \times 10^6 \text{ cm}^3)}{(299.82\text{K})(82.06)(0.83)}$$

$$= 15244.5 \text{ g mol}$$

$$\therefore \hat{V} = \frac{V}{n} = \frac{6.797 \times 10^6 \text{ cm}^3}{15244.5 \text{ g mol}} = 445.87 \frac{\text{cm}^3}{\text{g mol}}$$

$$\therefore V_{r1} = \frac{\hat{V}}{\hat{V}_{c1}} = \frac{445.87}{341.68} = 1.305$$

$$\therefore z_2 = 1.06$$

$$T_2 = \frac{T_1 z_1 p_2}{z_2 p_1} = \frac{540^\circ\text{R}(0.83)(3014.7 \text{ psia})}{1.06(1964.7 \text{ psia})}$$

$$T_2 = 649^\circ\text{R} \quad (189^\circ\text{F})$$

14.18

Use $pV = znRT$ $p_c = 37.2 \text{ atm}$, $T_c = 132.5\text{K}$

$$@ \text{ state 2} \quad p_r = \frac{142.9}{37.2} = 3.84 \quad T_r = \frac{300}{132.5} = 2.26$$

Solutions Chapter 14

$$@ \text{ state 3} \quad p_r = \frac{142.9}{37.2} = 3.84 \quad T_r = \frac{973}{132.5} = 7.34$$

$$z_2 \approx 0.99$$

$$z_3 = 1.05$$

$$\frac{n_3}{n_2} = \left(\frac{p_1}{p_2} \right) \left(\frac{V_1}{V_2} \right) \left(\frac{R}{R} \right) \frac{(300)(0.99)}{973 (1.05)} = \boxed{0.29}$$

If you use the Pitzer acentric factor, ω for air is about 0.036

$$z = z^0 + z^1\omega$$

$$z_2 = 0.999 + 0.22 (0.036) = 1.00$$

$$z_3 = 1.05 + 0.03 (0.036) = 1.05$$

14.19

Basis: Gas at 50 atm and 600°R

From the compressibility charts:

$$p_r = \frac{50}{14.3} = 3.5$$

$$T_r = \frac{600}{40.0 + 460} = 1.2$$

$$z = 0.58$$

$$Q = \frac{100,000 \text{ std ft}^3}{\text{hr}} \left| \frac{1 \text{ lb mol}}{359 \text{ std ft}^3} \right| \frac{359(0.58) \text{ act ft}^3}{1 \text{ lb mol}} \left(\frac{1}{50} \right) \frac{600}{492} = \boxed{1415 \text{ actual ft}^3/\text{hr}}$$

or use $pV = znRT$ twice

(continued)

Solutions Chapter 14

$$\frac{p_2 V_2}{p_1 V_1} = \frac{z_2 n_2 R T_2}{z_1 n_1 R T_1}$$

$$\begin{aligned} V_2 &= V_1 \left(\frac{T_2}{T_1} \right) \left(\frac{p_1}{p_2} \right) \left(\frac{z_2}{z_1} \right) \\ &= 100,000 \left(\frac{600}{492} \right) \left(\frac{1}{50} \right) \left(\frac{0.58}{1.00} \right) \\ &= 1415 \text{ actual ft}^3/\text{hr} \end{aligned}$$

14.20

Basis: initial gas at 200 psig and final gas at 1000 psig

MW $C_2H_4 = 28$

$$p_{r1} = \frac{214.7/14.7}{50.5} = 0.290$$

$$T_r = 1.05$$

$$z_1 = 0.90$$

$$p_{r2} = \frac{1015/14.7}{50.5} = 1.37$$

$$T_r = 1.05$$

$$z_2 = 0.35$$

Use $pV = znRT$

$$\frac{n_2}{n_1} = \frac{p_2}{p_1} \left(\frac{z_2}{z_1} \right)^{-1} = \frac{1015}{215} \left(\frac{0.35}{0.90} \right)^{-1} = 12.14$$

Alternate way to get z is to use the Pitzer acentric factor.

$$z = z^0 + z^1 \omega$$

(continued)

Solutions Chapter 14

$$z_1 = 0.910 + (-0.023)(0.085) = 0.91$$

$$z_2 = 0.37 + (0.1059)(0.085) = 0.38$$

Material balance

$$W_1 + W_c = 222$$

$$W_2 - W_1 = 28 \text{ lb} \quad n_2 - n_1 = 28/28 = 1 \quad (\text{II})$$

$$W_2 + W_c = 250$$

Solve (I) and (II) to yield $n_1 = 0.089$

$$\text{and } n_2 = 1.089$$

a. Mass of gas initially = $(0.089)(28) = 2.49 \text{ lb}$

$$(28 \text{ lb}) (\$0.41/\text{lb}) = \$11.48 \text{ billing}$$

b. Wt. of cylinder = $(222 - 2.49) \text{ lb} = 219.5 \text{ lb}$

c.
$$V = \frac{n_1 z_1 R T}{p_1} = \frac{0.089 [0.91] [0.73] [298(1.8)]}{214.7} = 2.17 \text{ ft}^3$$

14.21

Basis: 33.6 lb gas

$$\begin{aligned} T &= 180^\circ\text{F} (640^\circ\text{R}) \\ P &= 2400 + 14.7 = 2415 \text{ psia} \end{aligned}$$



$$pV = znR$$

Basis: 100 mol gas

(continued)

Solutions Chapter 14

	mol	mol.wt.	lb	
CO ₂	10	44	440	
CH ₄	40	16	640	avg. mol wt. = $\frac{2480}{100} = 24.8$
C ₂ H ₄	50	28	1400	
	100	2560		

$$n = \frac{33.6}{24.8} = 1.35 \text{ lb mol}$$

$$T_c' = 0.10 (304.2) + 0.40 (190.7) + 0.50 (283.1) = 248.25 \text{ K}$$

$$p_c' = 0.10 (72.9) + 0.40 (45.8) + 0.50 (50.5) = 50.86 \text{ atm}$$

$$p_r' = \frac{p}{p_c} = \frac{2415}{(50.86)(14.7)} = 3.23$$

$$T_r' = \frac{T}{T_c} = \frac{640}{(248.25)(1.8)} = 1.43$$

From Fig. in text, $z \approx .75$

$$V = \frac{znRT}{p} = \frac{0.75 \left[1.35 \text{ lb mol} \right] \left[10.73 (\text{psia}) \left(\frac{\text{ft}^3}{(\text{lb mol})(^\circ\text{R})} \right) \right] \left[640^\circ\text{R} \right]}{2415 \text{ psia}}$$

$$= \boxed{2.88 \text{ ft}^3 \text{ at } 180^\circ\text{F, } 2415 \text{ psia of gas is cylinder volume}}$$

Solutions Chapter 14

14.22

0.20 EtOH
0.80 CO₂
1.00



$T = 500\text{K}$
 $V = 180 \text{ cm}^3/\text{g mol}$
 $p = ?$

Basis: gas as above

$$p_c' = (0.20) (63.0) + (0.80) (72.9) = 70.92 \text{ atm}$$

$$T_c' = (0.20) (516.3) + (0.80) (304.2) = 346.6 \text{ K}$$

$$p_r' = ? = \frac{p}{p_c} = \frac{p}{70.92}$$

$$T_r' = \frac{500}{346.6} = 1.44$$

$$V_{ci}' = \frac{RT_c'}{p_c} = \frac{(1 \text{ atm})(22.4 \text{ L}) \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right| \left| \frac{346.6 \text{ K}}{70.92 \text{ atm}} \right|}{(273 \text{ K})(1 \text{ g mol})} = 401 \text{ cm}^3/\text{g mol}$$

$$V_{ci}' = \frac{180}{401} = 0.45$$

From the compressibility chart, $p_r \approx 2.5$, $p \approx \boxed{177 \text{ atm}}$

Solutions Chapter 14

14.23

Basis: 540 kg gas @ 393 K, 3500 kPa absolute

Component	kg	kg mol	mole fraction	p_c , atm	T_c , K
CH ₄	100	6.25	0.321	45.8	191
C ₂ H ₆	240	8.00	0.412	48.2	305
C ₃ H ₈	150	3.41	0.175	42.1	370
N ₂	<u>50</u>	<u>1.79</u>	<u>0.092</u>	33.5	126
Total	540	19.45	1.000		

$$T_c' = (0.321)(191) + (0.412)(305) + (0.175)(370) + (0.092)(126) = 262.8 \text{ K}$$

$$p_c' = (0.321)(45.8) + (0.412)(48.2) + (0.175)(42.1) + (0.092)(33.5) = 44.96 \text{ atm}$$

$$T_r' = \frac{3.93}{262.8} = 1.50$$

$$p_r' = \frac{3500}{44.96} \frac{1 \text{ atm}}{101.3} = 0.77$$

From Nelson and Obert Chart, $z' = 0.935$

$$\text{MW (average)} = 540/19.45 = 27.8 \text{ kg/kg mol}$$

$$\rho = \frac{3500 \text{ kPa}}{393 \text{ K}} \frac{27.8 \text{ kg}}{0.935} \frac{(\text{K})(\text{kg mol})}{\text{kg mol} \cdot 8.31 (\text{kPa})(\text{m}^3)}$$

$$= \frac{31.9 \text{ kg}}{\text{m}^3 \text{ at } 393 \text{ K and } 3500 \text{ kPa}}$$

Solutions Chapter 14

14.24

Use Kay's Method

$$p_c' = \sum n_i p_{c,i}; T_c' = \sum n_i T_{c,i}$$

Component	n	p_c	$n p_c$	T_c	$n T_c$
C ₂ H ₄	0.57	50.5	28.8	283	61.2
A	0.40	48.0	19.2	150.7	60.2
He	0.03	10.26	<u>0.308</u>	13.19	<u>0.395</u>

$$\sum n_i p_{c,i} = 48.31 \quad \sum n_i T_{c,i} = 221.8$$

$$p_r' = \frac{120}{48.3} = 2.49 \quad T_r' = \frac{298}{222} = 1.342 \quad \therefore z = 0.70$$

$$V = \frac{(0.70)(82.05)(298)}{(120)} = 142.8 \text{ cm}^3/\text{g mol}$$

$$\% \text{ diff} = \left(\frac{142.8 - 140}{140} \right) 100 = 2.00\%$$

Solutions Chapter 14

14.25

Basis: 30ft³ mixture of 100 atm and 300°F

Comp	Mol. frac	T_c	p_c	T'_c	p'_c
C ₂ H ₄	0.60	283	50.5	170	30.3
A	0.40	150.7	48	60.2	19.2
				230.2	49.5

$$T'_r = T/T'_c = \frac{760}{(230.2)(1.8)} = 1.835$$

$$p'_r = \frac{p}{p'_c} = \frac{100}{49.5} = 2.02$$

$$z = 0.95$$

$$\text{Avg. Mol. wt.} = (0.60)(28) + (0.40)(40) = 32.8 \text{ lb/lb mol}$$

$$pV = znRT$$

$$n = \frac{pV}{zRT} = \frac{(100)(14.7)(300)}{(0.95)(10.71)(760)} = 57.0 \text{ lb mol}$$

Assume capacities are given at storage conditions. Then type 1A is selected because it is the cheapest.

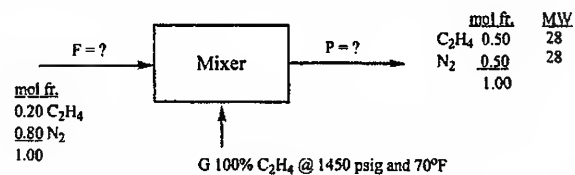
$$\text{Number of tanks required} = \frac{(57.0)(32.8)}{62} = \boxed{30}$$

Solutions Chapter 14

14.26

Steps 2, 3, and 4:

Assume a continuous process although a batch process would be acceptable and give the same results.



Step 5: Basis: G at given conditions

Steps 6 and 7:

Unknowns: F, P

Balances: C₂H₄, N₂, (or total) } degrees of freedom = 0

Steps 8 and 9:

Calculate G:

$$T_r = \frac{70 + 460}{508.3} = 1.044$$

$$p_r = \frac{1450 + 14.7}{735} = 1.992$$

$$z = 0.34$$

$$V = \frac{(359)(n)(14.7)(530)(0.34)}{(1465)(492)} = \frac{(2640)}{(1728)}$$

(continued)

Solutions Chapter 14

$$n = \frac{(2640)(1465)(492)}{(1728)(359)(14.7)(530)(0.34)} = 1.157 \text{ lb mol}$$

Balances:

$$\text{C}_2\text{H}_4 \quad F(0.20) + 1.157 = P(0.50)$$

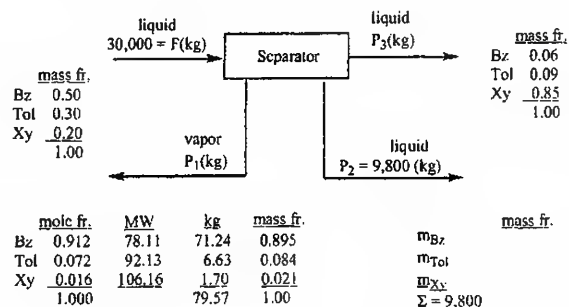
$$\text{Total} \quad F + 1.157 = P$$

$$F = 1.928 \text{ lb mol} \quad P = 3.085 \text{ lb mol}$$

14.27

Step 5: Basis: 1 hr.

Steps 2, 3, and 4: Steady state, open system



Convert F to moles and then to mass:

Solutions Chapter 14

Basis: 100 kg = F

Component	kg	MW	kg mol	mol fr.	T _c (K)	p _c (atm)
Bz	50	78.11	0.640	0.592	562.6	48.6
Tol	30	92.13	0.324	0.299	593.9	40.3
Xy	20	106.16	0.118	0.109	619	34.6
	100		1.082	1.000		

Calculate the kg of F; get z:

$$T'_c = 562.6 (0.592) + 593.9 (0.299) + 619 (0.109) = 578.1$$

$$p'_c = 48.6 (0.592) + 40.3 (0.299) + 34.6 (0.109) = 44.6$$

$$T_r = \frac{607\text{K}}{578.1\text{K}} = 1.05 \quad p_r = \frac{26.8\text{ atm}}{44.6\text{ atm}} = 0.60$$

$$z = 0.80$$

Together mass of feed:

$$n = \frac{pV}{zRT} = \frac{26.8\text{ atm}}{0.80} \left| \frac{483\text{ m}^3}{0.80} \right| \left| \frac{101.3\text{ kPa}}{1\text{ atm}} \right| \left| \frac{(\text{kg mol})(\text{K})}{8.314(\text{kPa})(\text{m}^3)} \right| \frac{1}{607\text{ K}}$$

$$= 324.7 \text{ kg mol}$$

$$F = (324.7) (100) / (1.082) = 30,017 \text{ kg, say } 30,000 \text{ kg}$$

The material balances are in kg.

Step 6: Unknowns: P₁, P₃, m_{Bz}, m_{Tol}, m_{Xy}

(continued)

Solutions Chapter 14

Step 7: Balances:

Bz

$$\text{Tol} \quad \frac{m_{Bz}}{m_{xy}} = \frac{3}{2} = 1.5$$

Xy

$$\Sigma m_i = 9,800$$

Step 8: The balances in kg are (only 3 are independent mass balances)

$$(1) \quad Bz \quad 30,000 (0.50) = P_1 (0.895) + m_{Bz} + P_3 (0.06)$$

$$(2) \quad \text{Tol:} \quad 30,000 (0.30) = P_1 (0.084) + m_{\text{Tol}} + P_3 (0.09)$$

$$(3) \quad Xy: \quad 30,000 (0.20) = P_1 (0.021) + m_{xy} + P_3 (0.85)$$

$$(4) \quad \text{Total} \quad 30,000 = P_1 + 9,800 + P_3$$

$$(5) \quad m_{Bz} + m_{\text{Tol}} + m_{xy} = 9800$$

$$(6) \quad m_{Bz} = 1.5 m_{xy}$$

Solutions Chapter 14

Step 9:

Solution: Using (1), (2), (3), (5), and (6) via Polymath

	kg	mass fr.
$P_3 = 5500 \text{ kg/hr}$	$m_{Bz} = 1518$	0.156
$P_1 = 14,700 \text{ kg/hr}$	$m_{\text{tol}} = 7270$	0.745
	$m_{xy} = 1012$	0.103
	9800	1.00

15.1

- 1.a Immediate but approximate
- 2.e Exact but requires access to a handbook
- 3.b Good accuracy, needs calculation of z
- 4.c Good accuracy, more complicated calculation than b even in a program with a data base
- 5.e May require a long search to filter out a good value
For other answers, look at the answer to P15.1.

15.2

Will get the most accurate value, and be quick, assuming you have the handbook that contains the required data. For other answers, look at the answer to P15.1.

15.3

Some valid answers are

- (1) continuous analytical functions, and these functions can be differentiated and integrated
- (2) higher accuracy (with complex equations)

15.4

$$z = 1 + \frac{B}{V} + \frac{C}{V^2} + \frac{D}{V^3}$$

The results for $\frac{p\hat{V}}{RT} = z$ are shown in the Excel table below. You can decide how much accuracy is needed.

p(atm)				% difference	
	4 terms	2 terms	1 term	2 from 4	1 from 4
0	1.00	1.00	1.00	0	0
10	0.95	0.95	1.00	0	-4.9
50	0.88	0.88	1.00	0	-13.3
100	0.77	0.76	1.00	-0.8	-29.8
200	0.80	0.79	1.00	1.6	-25.1
500	0.90	0.90	1.00	0	-10.7
1000	0.95	0.95	1.00	0	-3.6
5000	0.99	0.99	1.00	0	-1.1

15.5

Basis: 460 kg CO₂

a. RK Equation:

$$\frac{460 \text{ kg CO}_2}{44 \text{ kg}} \left| \frac{1 \text{ kg mol}}{44 \text{ kg}} \right| = 10.455 \text{ kg mol CO}_2$$

$$T_c = 304.2 \text{ K}, p_c = 7385 \text{ kPa}$$

$$a = 6458 \text{ (kPa)} (\text{m}^6) (\text{K}^{0.5}) / (\text{kg mol})^2$$

$$b = 0.0297 \text{ m}^3 / \text{kg mol}$$

$$R = 8.314 \frac{(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}$$

$$\hat{V} = \frac{V}{n} = \frac{10.4 \text{ m}^3}{10.455 \text{ kg mol}} = 0.995 \frac{\text{m}^3}{\text{kg mol}}$$

$$p = \frac{(8.314)(290)}{0.995 - 0.0297} - \frac{6458}{0.995(0.995 + 0.0297)(290)^{1/2}}$$

(continued)

Solutions Chapter 15

$$= 2.126 \times 10^3 \text{ kPa}$$

b. SRK Equation:

$$\text{Data as above: } T/T_c = 290/304.2 = 0.953$$

$$a' = \frac{0.42748(8.314)^2 (304.2)^2}{7358} = 379.2 (\text{kPa})(\text{m}^3)/(\text{kg mol})^2$$

$$b = \frac{0.08664(8.314)(304.2)}{7358 \times 10^3} = 0.0297 \text{ m}^3/\text{kg mol}$$

$$p = \frac{(8.314)(290)}{0.995 - 0.0297} - \frac{(379.2)(1.040)}{0.995(0.995 + 0.0297)}$$

$$\kappa = 0.480 + (1.574)(0.225) - 0.176(0.225)^2 = 0.843$$

$$\lambda = [1 + 0.843(1 - 0.953^2)]^2 = 1.040$$

$$p = 2.111 \times 10^3 \text{ kPa} \quad \text{No significant difference.}$$

15.6

$$a \Rightarrow (\text{atm}) \left(\frac{\text{L}}{\text{g mol}} \right)^2$$

$$b \Rightarrow \text{L/g mol}$$

$$\alpha \Rightarrow \text{dimensionless}$$

Solutions Chapter 15

15.7

Redlich-Kwong

$$p = \frac{RT}{(\hat{V} - b)} - \frac{a}{T^{1/2} \hat{V}(\hat{V} + b)}$$

$$a = 86,870 \text{ psia } (^{\circ}\text{R})^{1/2} (\text{ft}^3/\text{lb mol})^2$$

$$b = 0.3536 \text{ ft}^3/\text{lb mol}$$

$$n = \frac{63.9}{32} = 1.997 \text{ lb mol}$$

$$\hat{V} = \frac{V}{n} = \frac{6.7}{1.997} = 3.355 \text{ ft}^3/\text{lb mol}$$

$$\text{Solving, } p = 1335 \text{ psia}$$

Therefore, the reading on the pressure gauge is incorrect.

15.8

Basis: 100 ft³ of NH₃ at 20 atm and 400°FPart I. Calculate the moles of NH₃:

Data:

$$T_c = 405.3 \text{ K} \rightarrow 729.5^{\circ}\text{R}$$

$$P_c = 111.3 \text{ atm} \rightarrow 1636 \text{ psia}$$

$$\omega = 0.250 \quad 400^{\circ}\text{F} \rightarrow 860^{\circ}\text{R}$$

$$R = 10.73 (\text{psia})(\text{ft}^3)/(\text{lb mol})(^{\circ}\text{R}) \quad 20 \text{ atm} = 293.9 \text{ psia}$$

$$T_r = T/T_c = 860/729.5 = 1.179$$

(continued)

$$p = \frac{RT}{\hat{V} - b} - \frac{a\alpha}{\hat{V}(\hat{V} + b) + b(\hat{V} - b)}$$

$$\alpha = [1 + \kappa(1 - T_r^{1/2})]^2 = 0.9890$$

$$\kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2 = 0.1276$$

$$a = 0.45724 \left(\frac{R^2 T_c^2}{p_c} \right) = 17,124$$

$$b = 0.07780 \left(\frac{RT_c}{p_c} \right) = 0.3722$$

From Polymath:

$$\hat{V} = 29.9 \text{ ft}^3 / \text{lb mol}$$

$$\frac{100}{29.9} = 3.34 \text{ lb mol NH}_3 \rightarrow 56.8 \text{ lb NH}_3$$

Part II: Calculate the final pressure

$$\text{Final } \hat{V} = \frac{5 \text{ ft}^3}{3.34 \text{ lb mol}} = 1.497 \text{ ft}^3 / \text{lb mol}$$

$$350^\circ\text{F} \rightarrow 810^\circ\text{R}$$

Introduce $\hat{V}$ into the PR equation. From Polymath

$$p = \frac{(10.73)(810)}{1.497 - 0.3722} - \frac{17,124(0.984)}{1.497(1.497 + 0.3722) + 0.3722(1.497 - 0.3722)}$$

$$= \boxed{2462 \text{ psia}}$$

15.9

Basis: CO_2 at 81 psig and 25°C

Pressure in can (81.0 psig + 14.7 psia) (1 atm/14.7 psia) = 6.51 atm

Temperature $25^\circ\text{C} \Rightarrow 298.15\text{K}$

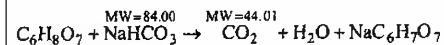
$$T_c = 304.2 \text{ K}$$

$$V = \pi(4.05 \text{ cm})^2(17.0 \text{ cm}) = 876 \text{ cm}^3$$

$$p_c = 72.9 \text{ atm}$$

$n = ? \text{ CO}_2$

$$\omega = 0.225$$



Using Peng-Robinson equation

$$n^3(ba\alpha - b^2RT - b^3p) - n^2(V)(a\alpha - 2bRT - 3b^2p) - n(V^2)(bp - RT) - V^3p = 0$$

Equations $\Rightarrow$

$$f(n) = n^3q - n^2(V)(z) - n(V^2)(bp - RT) - V^3p = 0$$

$$q = ba\alpha - b^2RT - b^3p$$

$$z = a\alpha - 2bRT - 2b^2p$$

$$a = 0.45724 \left(\frac{R^2 T_c^2}{p_c} \right) = 3.908 \times 10^6$$

$$b = 0.07780(RT_c / p_c) = 26.64$$

$$T_r = 298.15/304.2 = 0.980$$

$$(T_r)^{1/2} = 0.990$$

$$\alpha = [1 + \kappa(1 - (T/T_c)^{1/2})]^2 = 1.007$$

$$\kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2 = 0.7080$$

(continued)

Solutions Chapter 15

$$R = 82.06 \text{ (cm}^3\text{)(atm)(g mol)}^{-1}\text{(K)}$$

The ideal gas law gives 0.233 mol CO₂

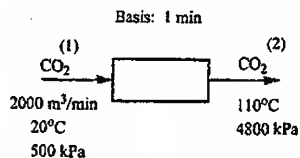
$$T = 298.18\text{K}$$

$$p = 6.51 \text{ atm}$$

Introduce the values into the PR equation to get $n = 0.2420 \text{ mol CO}_2$

$$\frac{0.2420 \text{ mol CO}_2}{1 \text{ mol CO}_2} \left| \frac{1 \text{ mol NaHCO}_3}{1 \text{ mol CO}_2} \right| \frac{84.00 \text{ g NaHCO}_3}{1 \text{ mol NaHCO}_3} = \boxed{20.3 \text{ g NaHCO}_3}$$

15.10



Calculate the moles entering the compressor:

$$p_1 = \frac{500}{101.3} \text{ atm} = 0.068$$

$$T_1 = \frac{(20 + 273)\text{K}}{304.2 \text{ K}} = 0.96$$

$$p_2 = \frac{4800}{101.3} \text{ atm} = 0.650$$

$$T_2 = \frac{(110 + 273)\text{K}}{304.2 \text{ K}} = 1.26$$

$$a = 3.6 \times 10^6 \text{ atm} \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2 = 364.68 \text{ kPa} \left(\frac{\text{m}^3}{\text{kg mol}} \right)^2$$

Solutions Chapter 15

$$b = 42.8 \frac{\text{cm}^3}{\text{g mol}} = 0.0428 \frac{\text{m}^3}{\text{kg mol}}, \quad R = 8.314 \frac{(\text{kPa})(\text{m}^3)}{(\text{kg mol})(\text{K})}$$

Use Van der Waals' equation:

$$\left(p + \frac{n^2 a}{V^2} \right) (V - nb) = nRT$$

As the initial guess for the number of moles in State 1 use the ideal gas law

$$n_1 = \frac{p_1 V_1}{RT_1} = \frac{(500)(2000)}{(8.314)(293)} = 410.5 \text{ kg mol}$$

The number of moles at condition (1) is obtained from

$$\left(500 + \frac{n_1^2 (364.68)}{2000^2} \right) (2000 - 0.0428 n_1) = (8.314)(293)n_1$$

From Polymath (on the CD)

$$n_1 = \boxed{420 \text{ kg mol}}$$

Calculate the m³ exiting the compressor:

Insert into Vander Waals' equation new parameters:

$$p = 4800 \text{ kPa} \quad T = 383 \text{ K} \quad n = 420 \text{ kg mol}$$

Solve for V

$$V = \boxed{246 \text{ m}^3 \text{ at } 383\text{K and } 4800 \text{ kPa}}$$

Solutions Chapter 15

15.11

$$p_{\text{abs}} = p_g + \text{barometric pressure} \quad T = 273 - 50 = 223 \text{ K}$$

$$p_{\text{abs}} = 39 + 1 = 40 \text{ atm}$$

Basis: 1 g mol H_2

H_2 Coefficients

	a	b
Van der Waals	$0.246 \times 10^6 (\text{atm})(\text{cm})^6 / (\text{g mol})^2$	$26.6 (\text{cm})^3 / \text{g mol}$
Redlich-Kwong	$1.439 \times 10^6 (\text{atm})(\text{K}^{1/2})(\text{cm})^6 / (\text{g mol})^2$	$18.5 (\text{cm})^3 / \text{g mol}$

Computer results

Van der Waals: $471.78 \text{ cm}^3 / \text{g mol}$

Redlich-Kwong $471.26 \text{ cm}^3 / \text{g mol}$

$$\frac{5L}{1} \left| \frac{1000 \text{ cm}^3}{L} \right| \frac{1 \text{ g mol}}{471.78 \text{ cm}} = 10.60 \text{ g mol (van der Waals)}$$

$$5 (1000) / 471.26 = 10.61 \text{ g mol (Redlich - Kwong)}$$

15.12

For propane: $T_c = 369.9 \text{ K}$, $p_c = 42.0 \text{ atm}$, $\omega = 0.152$

$$\kappa = 0.37464 + 1.5422(0.152) - 0.26992(0.152)^2 = 0.60283$$

Solutions Chapter 15

$$\alpha = [1 + 0.60283(1 - 1.00686)]^2 = 0.992$$

Propane Coefficients

	a	b
RK	$180.5 \times 10^6 (\text{atm})(\text{K}^{1/2})(\text{cm})^6 / (\text{g mol})^2$	$62.7 \text{ cm}^3 / \text{g mol}$
PR	$10.04 \times 10^6 (\text{atm})(\text{cm})^6 / (\text{g mol})^2$	$56.3 \text{ cm}^3 / \text{g mol}$

Computer results:

Redlich-Kwong: $1193.14 \text{ cm}^3 / \text{g mol}$

Peng-Robinson: $1168.91 \text{ cm}^3 / \text{g mol}$

Determine the volume at condition of state 2 (383 K, 4800 kPa)

$$\left(4800 + \frac{(419.9)^2 (364.68)}{V_2^2} \right) (V_2 - (0.0428)(419.9)) = (419.9)(8.314)(383)$$

$$V = 246 \text{ m}^3 \text{ at state 2}$$

15.13

For CO_2 , $\omega = 0.225$ and $T_c = 304.2 \text{ K}$, $p_c = 72.9 \text{ atm}$

$$a = 62.75 \times 10^6 (\text{atm})(\text{K}^{1/2})(\text{cm})^6 / (\text{g mol})^2$$

$$b = 29.9 \text{ cm}^3 / \text{g mol}$$

Computer results:

Redlich-Kwong = $1559.6 \text{ cm}^3 / \text{g mol}$

(continued)

Solutions Chapter 15

$$\text{The experimental molar volume} = \frac{6250 \text{ cm}^3}{4 \text{ g mol}} = \boxed{1562.5 \text{ cm}^3/\text{g mol}}$$

15.14

For CO_2 , $\omega = 0.225$ and $T_c = 304 \text{ K}$, $p_c = 72.9 \text{ atm}$ or 7385 kPa

$$\begin{aligned} R &= 8.314 \text{ (kPa)} (\text{m}^3)/(\text{kg mol}) (\text{K}) \\ a &= 6458 \text{ (kPa)} (\text{m}^6) (\text{K}^{0.5})/(\text{kg mol})^2 \\ b &= 0.0297 \text{ m}^3/(\text{kg mol}) \end{aligned}$$

$$1200 = \frac{(8.314)(290)}{(\hat{V} - 2.97 \times 10^{-2})} - \frac{6458}{\hat{V}(\hat{V} + 2.97 \times 10^{-2})(290)^{1/2}}$$

$$\hat{V} = 1.876 \text{ m}^3/\text{kg mol} \text{ from Polymath}$$

$$n_{\text{CO}_2} = \frac{V}{\hat{V}} = \frac{10.4}{1.876} = 5.54 \text{ kg mol}$$

$$n_{\text{CO}_2} = \frac{5.54 \text{ kg mol}}{1 \text{ kg mol}} \left| \frac{48 \text{ kg}}{1 \text{ kg mol}} \right| = \boxed{266 \text{ kg CO}_2}$$

15.15

$$p = \frac{nRT}{V - nb} - \frac{n^2 a}{V^2} \quad T = 492.0^\circ \text{R}$$

$$a = \left(p - \frac{nRT}{V - nb} \right) \left(-\frac{V^2}{n^2} \right) \quad R = 0.7302 \frac{(\text{ft}^3)(\text{atm})}{(\text{lb mol})(^\circ \text{R})}$$

Basis: 1.0 lb mol

Solutions Chapter 15

$$200 \text{ atm} = \frac{1.0 \text{ lb mol} \left| 0.7302 \frac{(\text{ft}^3)(\text{atm})}{(\text{lb mol})(^\circ \text{R})} \right| 492.0^\circ \text{R}}{(1.806 \text{ ft}^3 - (1.0 \text{ lb mol})b)} - \frac{(1.0 \text{ lb mol})^2 a}{(1.86 \text{ ft}^3)^2}$$

$$200 = \frac{359.3(\text{ft}^3)(\text{atm})}{(1.860 \text{ ft}^3 - b)} - 0.2891 a$$

similarly

$$1000 = \frac{359.3(\text{ft}^3)(\text{atm})}{(0.741 \text{ ft}^3 - b)} - 1.82a$$

$$a = \left(1000 - \frac{359.3}{0.741 - b} \right) \left(-\frac{1}{1.82} \right)$$

$$200 = \frac{359.3}{(1.860 - b)} - (0.289) \left(-\frac{1}{1.82} \right) \left(1000 - \frac{359.3}{0.741 - b} \right)$$

$$200 = \frac{359.3}{(1.860 - b)} + 158.8 - \frac{57.07}{(0.741 - b)}$$

$$41.20 = \frac{359.3}{(1.860 - b)} - \frac{57.07}{(0.741 - b)}$$

$$\begin{aligned} b &= 0.4808 \frac{\text{ft}^3}{\text{lb mol}} \\ a &= 209.3(\text{atm}) \left(\frac{\text{ft}^3}{\text{lb mol}} \right)^2 \end{aligned}$$

Solutions Chapter 15

15.16

a. Solution by compressibility factor method:

Basis: 80 lb water at 900°K

$$\hat{V} = \frac{10 \text{ ft}^3}{80 \text{ lb}} \left| \frac{18 \text{ lb}}{1 \text{ lb mol}} \right| \frac{1 \text{ cm}^3/\text{g mol}}{0.016 \text{ ft}^3/\text{lb mol}} = 140.8 \text{ cm}^3/\text{g mol}$$

$$T_c = 647.4 \text{ K}; \quad p_c = 218.3 \text{ atm from Appendix D1 (217.6 atm for the CD)}$$

$$V_a = \frac{RT_c}{p_c} = \frac{82.06(\text{cm}^3)(\text{atm})}{(^{\circ}\text{K})(\text{g mol})} \frac{647.4 \text{ K}}{218.3 \text{ atm}} = 243 \text{ cm}^3/\text{g mol}$$

$$V_r = \frac{\hat{V}}{V_a} = \frac{140.8}{243} = 0.579; \quad T_r = \frac{T}{T_c} = \frac{900}{647.4} = 1.39$$

From the compressibility charts, $p_r = 1.9$

$$p = p_r p_c = (1.9)(218.3) = \boxed{415 \text{ atm}}$$

b. solution using the Redlich-Kwong equation of state:

$$p = \frac{RT}{(\hat{V}-b)} - \frac{a}{T^{1/2} \hat{V}(\hat{V}+b)} \quad \text{where } a = 0.4278 \frac{R^2 T_c^{2.5}}{p_c} \\ b = 0.0867 \frac{RT_c}{p_c}$$

$$a = \frac{0.4278 \left[\frac{82.06(\text{cm}^3)(\text{atm})}{(\text{K})(\text{g mol})} \right]^2 (647.4 \text{ K})^{2.5}}{218.3 \text{ atm}} = 1.407 \times 10^8 \frac{(\text{cm}^3)^2 (\text{atm})(\text{K})^{1/2}}{(\text{g mol})}$$

Solutions Chapter 15

$$b = \frac{0.0867 \left[\frac{82.06(\text{cm}^3)(\text{atm})}{(\text{K})(\text{g mol})} \right] 647.4 \text{ K}}{218.3 \text{ atm}} = 21.1 \frac{\text{cm}^3}{\text{g mol}}$$

$$p = \frac{(82.06)(900)}{(140.8 - 21.1)} - \frac{1.407 \times 10^8}{(900)^{1/2} (140.8)(140.8 + 21.1)} = (617 - 206) \text{ atm} \\ = \boxed{411 \text{ atm}}$$

15.17

For ethane: $T_c = 516.3$ and $p_c = 63.0 \text{ atm}$

a. Use Van der Waals' equation.

Basis: Ethane at 100°F and 2000 psig (MW = 30)

$$p = 2014.7 \text{ psia} \quad V = 1.0 \text{ ft}^3 \quad T = 560^{\circ}\text{R}$$

$$a = \left(5.50 \times 10^6 \text{ atm} \left(\frac{\text{cm}^3}{\text{g mol}} \right)^2 \right) \left(3.776 \times 10^{-3} \right) = 2.07 \times 10^4 \text{ psia} \left(\frac{\text{ft}^3}{\text{lb mol}} \right)^2$$

$$b = \left(65.1 \frac{\text{cm}^3}{\text{g mol}} \right) \left(1.60 \times 10^{-2} \right) = 1.04 \frac{\text{ft}^3}{\text{lb mol}}$$

$$\left(p + \frac{an^2}{V^2} \right) \left(\frac{V}{n} - b \right) = RT$$

$$n^3 \left(\frac{ba}{V^2} \right) - n^2 \left(\frac{a}{V} \right) + n(pb + RT) - pV = 0$$

$$n^3 - 0.962n^2 + 0.376n - 0.0936 = 0$$

Iterate to find value of n.

Use Excel to solve this cubic equation to obtain a positive, real answer. (continued)

Solutions Chapter 15

$$n = 0.594 \text{ lb mol or } \boxed{17.8 \text{ lb ethane}}$$

b. Use the compressibility factor method.

P_c	T_c	P_r	T_r	z from the compressibility charts
709 psia	549°R	2.84	1.02	0.43

$$\text{mass} = \frac{1(\text{ft})^3}{560^\circ\text{R}} \left| \frac{2014.7 \text{ psia}}{0.43} \right| \left| \frac{(^{\circ}\text{R})(\text{lb mol})}{10.73(\text{psia})(\text{ft})^3} \right| \left| \frac{30 \text{ lb}}{\text{mol}} \right| = \boxed{23.4 \text{ lb ethane}}$$

15.18

a. Van der Waals equation

$$a = \left(\frac{27}{64} \right) \frac{R^2 T_c^2}{P_c} \quad b = \left(\frac{1}{8} \right) \frac{R T_c}{P_c}$$

Methane	$T_c = 190.7\text{K}$	$p_c = 45.8 \text{ atm}$
Propane	$T_c = 369.9\text{K}$	$p_c = 42.0 \text{ atm}$

$$\text{Methane: } \frac{190.7}{45.8} = 4.16 \quad \text{Propane: } \frac{369.9}{42.0} = 8.81$$

Propane will be higher
for both coefficients

b. SRK equation:

$$a' = \frac{0.42748 R^2 T_c}{P_c} \quad b = \frac{0.08664 R T_c}{P_c}$$

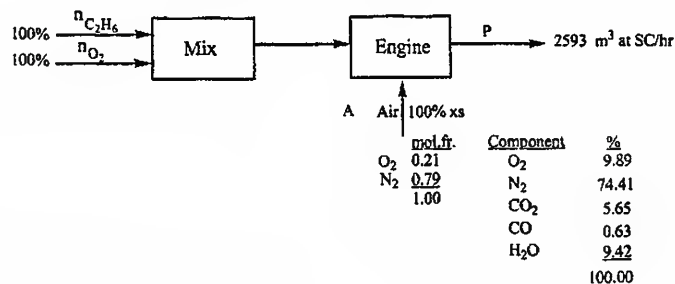
Solutions Chapter 15

Answer is same as for (a); propane
will be higher for both coefficients

15.19

Steps 2, 3, and 4:

System: Mixer plus engine, open, steady state



Step 5: Basis: 1 hr = 2593 m³ at SC

$$\frac{259}{22.415} = 115.68 \text{ kg mol in P}$$

Steps 6 and 7:

Unknowns: $n_{C_2H_6}, n_{O_2}, A$ } degrees of freedom = 0 - 1; one

Element balances: C, N, H, O } equation is redundant if the equations are independent

(continued)

Solutions Chapter 15

$$\text{C: } n_{\text{C}_3\text{H}_8}(2) = 115.68(0.0565 + 0.0063) = 7.265 \quad n_{\text{C}_3\text{H}_8} = 3.632 \text{ kg mol}$$

$$2\text{N: } A(0.79) = 115.68(0.7441) \quad A = 108.96 \text{ kg mol}$$

$$2\text{O: } n_{\text{O}_2} + (108.96)(0.21) = 115.68 \left(0.0989 + 0.0565 + \frac{0.0063}{2} + \frac{0.0942}{2} \right)$$

$$n_{\text{O}_2} = 0.908 \text{ kg mol}$$

$$T = -18^\circ\text{C} = 255.6 \text{ K} \quad V = 0.190 \text{ m}^3 \quad (0.190 \times 10^6 \text{ cm}^3)$$

Use Van der Waals' equation:

$$p = \frac{nRT}{V-nb} - \frac{n^2a}{V^2} \quad a = 1.36 \times 10^6 \frac{(\text{atm})(\text{cm}^6)}{(\text{g mol})^2} \rightarrow 1.377 \times 10^7 \frac{(\text{kPa})(\text{m}^6)}{(\text{kg mol})^2}$$

$$b = 31.9 \frac{\text{cm}^3}{\text{g mol}} \rightarrow 0.0319 \frac{\text{m}^3}{\text{kg mol}}$$

$$\text{Solution: } p = 1.013 \times 10^4 \text{ kPa}$$

Use Redlich-Kwong equation:

$$p = \frac{RT}{\hat{V}-b} - \frac{a}{T^{1/2}\hat{V}(\hat{V}+b)} \quad a = 15.65 \times 10^6 \frac{(\text{atm})(\text{K}^{1/2})(\text{cm}^6/\text{g mol})^2}{(\text{g mol})^2}$$

$$b = 25.3 \frac{\text{cm}^3}{\text{g mol}}$$

$$\hat{V} = \frac{0.190 \text{ m}^3}{0.9086 \text{ kg mol}} = 0.209 \frac{\text{m}^3}{\text{kg mol}}$$

Solution using Polymath

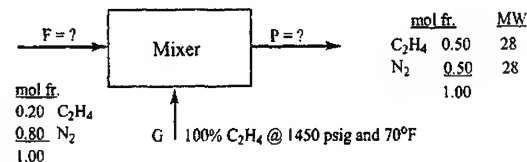
$$p = 1.01 \times 10^4 \text{ kPa}$$

Solutions Chapter 15

15.20

Assume a continuous process although a batch process would be acceptable and give the same results.

Steps 2, 3, and 4:



Step 5: Basis: G at given conditions

Steps 6 and 7:

Unknowns: F, P
Balances: C_2H_4 , N_2 (or total) } degrees of freedom = 0

Steps 8 and 9:

Calculate G: Use Van der Waals' equation

$$p = \frac{1465}{14.7} = 99.8 \text{ atm}$$

$$R = 82.06 \frac{(\text{atm})(\text{cm}^3)}{(\text{K})(\text{g mol})}$$

$$T = \frac{530}{1.8} = 294.5 \text{ K}$$

C_2H_4 :

$$a = 4.48 \times 10^6 \text{ atm}(\text{cm}^3/\text{g mol})^2$$

$$b = 57.2 \text{ cm}^3/\text{g mol}$$

N_2 :

$$a = 1.347 \times 10^6$$

$$b = 38.6$$

(continued)

Solutions Chapter 15

$$V = \frac{2640}{1} \left(\frac{2.54}{1} \right)^3 = 43,262 \text{ cm}^3$$

$$\left(p + \frac{n^2 a}{V^2} \right) \left(\frac{V}{n} - b \right) = RT$$

$$\left[99.8 + \frac{n^2 (4.48 \times 10^6)}{(43,262)^2} \right] \left[\frac{43,262}{n} - 57.2 \right] = (82.06)(294.5) = 24,167$$

Start with $n = 550 \text{ cm}^3$.

Polymath Results

NLE Solution

Variable	Value	f(x)	Ini Guess
n	756.04046	-4.776E-06	550

NLE Report (safenewt)

Nonlinear equations

$$[1] \quad f(n) = (99.8 * n + .00239 * n^3) * (43262 - 57.2 * n) - 24167 * n = 0$$

Settings

Max iterations = 150

Tolerance F = 0.0000001

Tolerance X = 0.0000001

Tolerance min = 0.0000001

$$\frac{756 \text{ g mol}}{454 \text{ g}} \left| \frac{1 \text{ lb}}{454 \text{ g}} \right| = 1.665 \text{ lb mol}$$

Balances

Let P be the lb mol of gas in the feed, and F be the lb mol of gas with 20% C₂H₄.

Solutions Chapter 15

$$\text{C}_2\text{H}_4: \quad F(0.20) + 1.665 = P(0.50)$$

$$\text{Total:} \quad F + 1.665 = P$$

$$F = 2.78 \text{ lb mol} \quad P = 4.40 \text{ lb mol}$$

Solutions Chapter 16

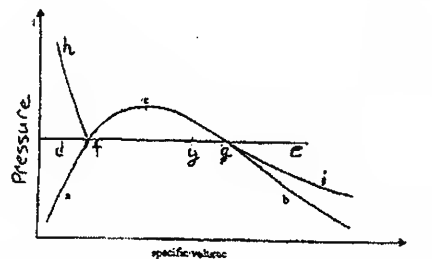
16.1

1. (1); 2. (2); 3. (3); 4. (4); 5. (3); 6. (1)

16.2

- (a) 40°C; (b) 190°C; (c) 60°C; (d) Compound B

16.3



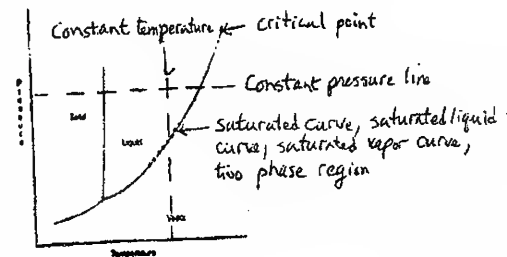
- (a) afcgb is the saturated curve
 (b) afc is the saturated liquid curve
 (c) cgh is the saturated vapor curve
 (d) hfa to the left is the liquid phase
 (e) hfcgb to the right is the vapor phase
 (f) afcgb below is the liquid vapor-region
 (g) c is the critical point

Solutions Chapter 16

(h) hfgi is a constant temperature line

(i) dfge is a constant pressure line

16.4



16.5 (e)

16.6 All true

16.7

- (a) higher; (b) lower; (c) higher; (d) lower; (e) no change; (f) lower;
 (g) higher; (h) lower; (i) higher; (j) lower; (k) lower; (l) higher

16.8

From the p-T diagram for water you can see that raising the pressure by a large amount on ice at constant temperature causes the water to go from the solid phase to the liquid phase.

Solutions Chapter 16

16.9

The vapor pressure of methanol is less than that of gasoline so that at lower temperatures the fuel-to-air mixture is insufficient for combustion.

Automotive parts can be made of alcohol tolerant materials such as stainless steel or other corrosion resistant materials and additives to the methanol, such as 15% gasoline, can help solve the problem of difficult cold-weather engine starts.

16.10

Appendix G (T is in K)	CD (T is in °C)
(a) Acetone at 0°C	
$\ln(p^*) = 16.6513 - \frac{2940.46}{T - 35.93}$	$\log_{10}(p^*) = 7.2316 - \frac{1277.03}{T + 237.23}$
$p^* = 70.51 \text{ mm Hg}$	$p^* = 70.55 \text{ mm Hg}$
(b) Benzene at 80°F	
$\ln(p^*) = 15.9008 - \frac{2788.51}{T - 52.36}$	$\log_{10}(p^*) = 6.90565 - \frac{1211.033}{T + 220.79}$
$p^* = 102.73 \text{ mm Hg}$	$p^* = 102.74 \text{ mm Hg}$
(c) Carbon tetrachloride at 300 K	
$\ln(p^*) = 15.8742 - \frac{2808.19}{T - 45.99}$	$\log_{10}(p^*) = 6.8941 - \frac{1219.58}{T + 227.17}$
$p^* = 123.81$	$p^* = 122.89 \text{ mm Hg}$

16.11

Fit the Antoine Equation using the three data points to get A, B, and C. In mm Hg

kPa	mm Hg
2.53	18.98
15.0	112.54
58.9	441.90

Solutions Chapter 16

$$\ln(18.98) = A - \frac{B}{C + (-40 + 273)} = 2.9434$$

$$\ln(112.54) = A - \frac{B}{C + (-10 + 273)} = 4.7233$$

$$\ln(441.90) = A - \frac{B}{C + (-20 + 273)} = 6.0911$$

The solution from Polymath is

$$A = 16.5386 \quad B = 2707.43 \quad C = -33.8541$$

$$\text{At } 40^\circ\text{C, } \ln(p^*) = 16.538 - \frac{2707.43}{-33.85 + (40 + 273)}$$

$$p^* = 939 \text{ mm Hg (125 kPa)}$$

16.12

At the triple point, all the phases (solid, liquid and vapor) exist in equilibrium. Therefore, the vapor pressure of liquid ammonia = the vapor pressure of solid ammonia

$$15.16 - 3063/T = 18.7 - 3754/T$$

$$\boxed{T = 195 \text{ K}}$$

16.13

No. It is a typo. Probably the number was 98.8°C because if you equate the pressures from the two equations, $T = 371.75\text{K}$, or 98.7°C.

Solutions Chapter 16

16.14

For benzene (p^* is in mm Hg and T in K)

$$\ln(p^*) = 15.9008 - \frac{2788.51}{T - 52.36} \quad p^* = 760 \text{ mm Hg} \quad \ln(p^*) = 6.6331$$

T = 353K agrees with data base on CD

For toluene

$$\ln(p^*) = 16.0137 - \frac{3096.52}{T - 53.67} \quad p^* = 760 \text{ mm Hg}$$

T = 383.7 agrees with data base on CD

16.15

Merge the two equations (AI MW = 27)

$$W = 10^{-4} = 5.83 \times 10^{-2} \frac{(p_v)(27)^{1/2}}{T^{1/2}} \quad \text{where } p_v = \frac{[10 \frac{(8.79 - \frac{1.594 \times 10^5}{T})}{T^{1/2}}]}$$

The solution from Polymath is

$$T = 1492K$$

Solutions Chapter 16

16.16

Log (T)	(log (T)) ²	DATA: (log (T)) ³	vp
5.6101	31.4727	176.5329	0.61130
5.7038	32.5331	185.5619	3.53600
5.7991	33.6295	195.0204	17.21000
5.8861	34.6462	203.9313	62.15000
5.9402	35.2856	209.6027	128.80000
5.9915	35.8976	215.0795	245.60000
6.0403	36.4847	220.3767	437.00000
6.0868	37.0488	225.5079	733.20000
6.1527	37.8561	232.9186	1454.00000
6.2146	38.6214	240.0166	2637.00000

$$\ln p^* = a + b \ln T + c(\ln T)^2 + d(\ln T)^3$$

THE COEFFICIENTS ARE

-1199.2548	a	-79.0261	c
532.2715	b	3.9638	d

16.17 Based on data from the steam tables:

State 1: liquid	State 3: solid	State 5: liquid (saturated)
State 2: superheated vapor	State 4: saturated vapor	State 6: vapor (saturated)

You can calculate the properties of a mixture of vapor and liquid in equilibrium (for a single component) from the individual properties of the saturated vapor and saturated liquid by averaging the properties of the two saturated phases. The weights are the respective amounts of each phase.

Solutions Chapter 16

16.18 Based on data from the steam tables:

State 1: saturated vapor State 3: two phase (saturated liquid and vapor)

State 2: saturated liquid State 4: superheated vapor

16.19

All of the values of specific volume are obtained using $\hat{V} = x_{\text{vapor}} \hat{V}_{\text{vapor}} + (1-x_{\text{vapor}}) \hat{V}_{\text{liquid}}$ with $\hat{V}$ data from the steam tables.

(a) $\hat{V} = 0.5 (1.673) + 0.5 (0.001043) = 0.837 \text{ m}^3/\text{kg}$

(b) $\hat{V} = 0.5 (0.6058) + 0.5 (0.001073) = 0.303 \text{ m}^3/\text{kg}$

(c) $\hat{V} = 0.3 (350.8) + 0.7 (0.01613) = 105.25 \text{ ft}^3/\text{lb}$

(d) $\hat{V} = 0.7 (1.8431) + 0.3 (0.0187) = 1.296 \text{ ft}^3/\text{lb}$

16.20

(a) T; (b) F; (c) T; (d) T; (e) F; (f) T

16.21

Use data from the steam tables at the initial condition of $p = 101.33 \text{ kPa}$ and saturated water (i.e. two phases):

$\hat{V}_{\text{liq}} = 1.044 \text{ cm}^3/\text{g}$ and $\hat{V}_{\text{vap}} = 1673.0 \text{ cm}^3/\text{g}$.

Then the mass of both phases in the container can be calculated:

Solutions Chapter 16

$$m_{\text{liq}} = (0.03 \text{ m}^3) (100 \text{ cm/m})^3 / 1.044 \text{ cm}^3/\text{g} = 28,376 \text{ g}$$

$$m_{\text{vap}} = 2.97 \text{ m}^3 (100 \text{ cm/m})^3 / 1673.0 \text{ cm}^3/\text{g} = 1,775 \text{ g}$$

$$m_{\text{total}} = 30,511 \text{ g}$$

At the final conditions all of the liquid has been evaporated, and only saturated vapor will exist having a specific volume of:

$$V_{\text{vap}} = (3.00 \text{ m}^3) (100 \text{ cm/m})^3 / 30,511 \text{ g} = 98.3 \text{ cm}^3/\text{g}$$

Interpolating in the steam tables

$$(212-T)^\circ\text{C} / (212-214)^\circ\text{C} = (99.09-98.3) \text{ cm}^3/\text{g} / (99.09-95.28) \text{ cm}^3/\text{g}$$

$$T = 212^\circ\text{C}$$

$$(1985.2\text{-}p) \text{ kPa} / (1985.2-2065.1) \text{ kPa} = (99.09-98.3) \text{ cm}^3/\text{g} / (99.09-95.28) \text{ cm}^3/\text{g}$$

$$p = 2002 \text{ kPa}$$

16.22

Basis: 10 lb of water

Specific volume: $\hat{V} = \frac{10.0}{2.01} = 4.975 \text{ ft}^3/\text{lb}$

From the paper steam tables (in ft^3/lb) at 80 psia:

$$\hat{V}_{\text{liq}} = 0.0176 \quad \hat{V}_{\text{vap}} = 5.476$$

Mass balance

$$m_L + m_V = 2.01$$

(continued)

Solutions Chapter 16

Volume balance

$$10.0 = m_L(0.0176) + m_V(5.476)$$

Mass of liquid is

$$0.184 \text{ lb}$$

Mass of vapor is

$$1.826 \text{ lb}$$

The volume of liquid is

$$V_{liq} = m_{liq} \hat{V}_{liq} = (0.184)(0.0176) = \boxed{3.28 \times 10^{-3} \text{ ft}^3}$$

The volume of vapor is

$$V_{vapor} = m_{vap} \hat{V}_{vapor} = 10.0 - 3.28 \times 10^{-3} = \boxed{9.997 \text{ ft}^3}$$

$$\text{Quality is: } 1.826 / 2.01 = \boxed{0.908}$$

16.23

Basis: 2.10 lb water

$$\text{Specific volume: } \hat{V} = (1-x) \hat{V}_l + x \hat{V}_g$$

$$\text{Specific volume of water} = \hat{V}_l = \frac{0.35}{2} = 0.175 \text{ m}^3/\text{kg}$$

From the steam tables:

Specific volume of saturated liquid,

$$\hat{V}_l = 0.001088 \text{ m}^3/\text{kg}$$

Solutions Chapter 16

specific volume of saturated vapor =

$$\hat{V}_g = 0.414 \text{ m}^3/\text{kg}$$

$$\text{Then, } 0.175 = (1-x) 0.001088 + x (0.414)$$

$$\text{The quality} = \boxed{x = 0.42}$$

16.24

Since the two phases coexist in equilibrium, we have a saturated mixture, and the pressure must be the saturation pressure at the given temperature:

$$p = p^* @ 90^\circ\text{C} = \boxed{70.14 \text{ kPa}}$$

$$\text{At } 90^\circ\text{C, } \hat{V}_l \text{ and } \hat{V}_g \text{ values are } \hat{V}_l = 0.001036 \text{ m}^3/\text{kg} \text{ and } \hat{V}_g = 2.361 \text{ m}^3/\text{kg}$$

Add the volume occupied by each phase:

$$\begin{aligned} V &= V_l + V_g = m \hat{V}_l + m_g \hat{V}_g \\ &= (8 \text{ kg})(0.001 \text{ m}^3/\text{kg}) + (2 \text{ kg})(2.361 \text{ m}^3/\text{kg}) = \boxed{4.73 \text{ m}^3} \end{aligned}$$

16.25

$$v = \frac{Q}{A} = \frac{m \hat{V}}{A}$$

where

v = velocity, ft/s

$\hat{V}$ = specific volume of the fluid, ft³/lb

A = pipe cross sectional area, ft²

(continued)

Solutions Chapter 16

$\hat{V}$ can be obtained from the steam tables: $\hat{V} = 0.9633 \text{ ft}^3/\text{lb}$

The area is $A = \pi d^2 / 4 = \frac{\pi}{4} \left(\frac{2.9}{12} \right)^2 = 0.046 \text{ ft}^2$

$$v = \frac{25,000 \text{ lb}}{\text{hr}} \left| \frac{0.9633 \text{ ft}^3}{\text{lb}} \right| \left| \frac{1}{0.046 \text{ ft}^2} \right| = 5.24 \times 10^5 \frac{\text{ft}}{\text{hr}} \text{ or } \boxed{145 \text{ ft/s}}$$

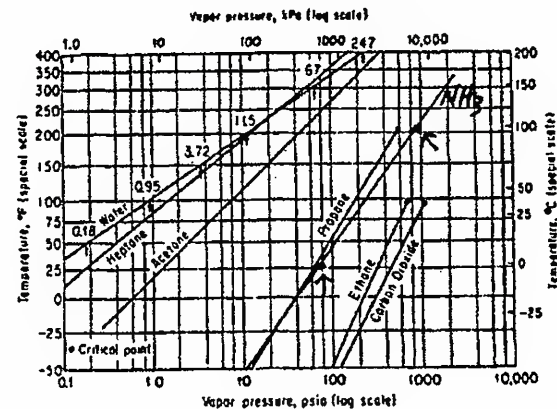
16.26

The hot oil vaporized the water, and the increase in volume in the system caused the damage.

16.27

Prepare a Cox chart as described in the text. Use semi-log paper with the horizontal axis $\log_{10}$. Obtain vertical scale rules by use of steam properties at even integers for the temperature. Or you can use Antoine Equation, Appendix G, to get 2 points and draw a line between them.

Solutions Chapter 16



	$T_{\text{critical}} (^{\circ}\text{F})$	$p_{\text{Cox chart}}^{\text{critical}} (\text{psia})$	$p^{\text{critical}} (\text{psia})$
(a) Acetone	454	670	691
(b) Heptane	512	700	397
(c) Ammonia	270	1500	1636
(d) Ethane	89.7	750	708

16.28

Steps for preparing a Cox Chart (using water as the reference substance):

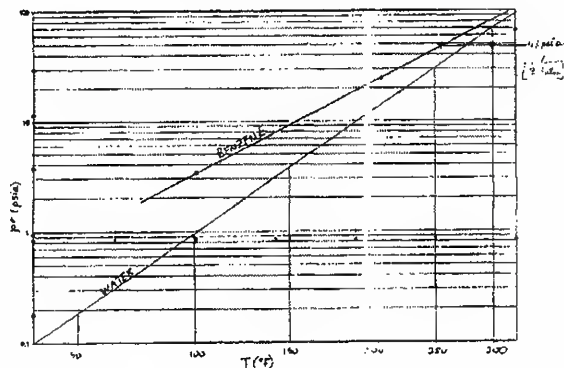
1. On logarithmic paper, set up the pressure scale on one axis. The other axis will be a nonlinear temperature scale which will be set up by the following method.
2. Draw a diagonal line from the origin to the opposite corner of the graph.
3. From the steam tables, obtain values for the vapor pressure of water at evenly spaced temperature increments.

(continued)

Solutions Chapter 16

- Plot these vapor pressures along the diagonal line.
- Now, beginning with the first point on the diagonal, draw a line extending from that point to the temperature axis and label the intersection as the corresponding temperature for that vapor pressure.
- Repeat step five for every point on the diagonal line. This process will establish the temperature scale.
- Using the established temperature scale, plot the data for benzene and draw a line through the points.
- From this line, obtain the vapor pressure for benzene at 125°F.

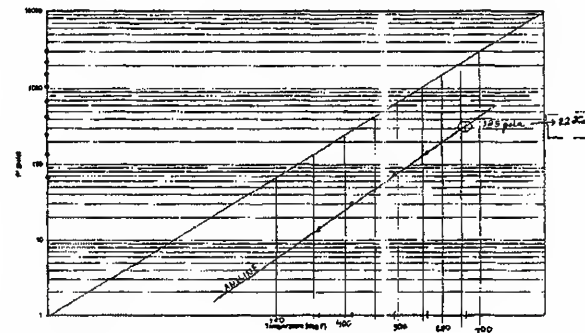
The vapor pressure for benzene at 125°C (257°F) is estimated to be 3.3 atm.



16.29

The procedure is the same as outlined for P16.28. The result from the Cox chart is that the vapor pressure for aniline at 350° is 22 atm.

Solutions Chapter 16



16.30

From the CD that accompanies the text the respective vapor pressures at 300K are in increasing value

	p^* in mm Hg	PEL (ppm)
Ethanol	65.8	1000
Methanol	139.7	200
MTBE	294	100

The relative values of p^* are about the same as the inverse of the relative values of the PEL.

Solutions Chapter 17

17.1

Basis: Data given in problem statement

H ₂ O	dry N ₂
27°C	27°C
p* = 3.536 kPa	p = 101.3 kPa

$$(a) p_T = p_{N_2} + p_{H_2O} = (101.3 + 3.536) \text{ kPa} = \boxed{104.8 \text{ kPa}}$$

$$(b) \frac{n_{H_2O}}{n_{N_2}} = \frac{p_{H_2O}}{p_{N_2}} = \frac{3.536 \text{ kPa}}{101.3 \text{ kPa}} = \boxed{0.0349}$$

17.2

T = -20°C
p* = 14.1 mm Hg

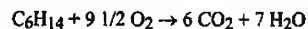
O ₂	p _i = 760 mm Hg
N ₂	p _{air} = 760 - 14.1 = 745.9 mm Hg
C ₆ H ₁₄	p _{C₆H₁₄} = p _{C₆H₁₄} = 14.1 mm Hg

Basis: 760 mol saturated gas (or use 100 mol)

p ⇒ moles

		mol
O ₂	.21 (745.9)	= 156.6
N ₂	.79 (745.9)	= 589.3
C ₆ H ₁₄		= 14.1
		760

For complete combustion



Solutions Chapter 17

$$156.6 - 134 = 22.60 \text{ mol } O_2 \text{ excess}$$

$$\frac{22.60}{134} \times 100 = \boxed{17\%}$$

17.3

(a) Volume increases

(b) Pressure increases

17.4

$$\text{mol. wt. } CCl_3NO_2 = 164.5$$

Basis: 1 mol saturated gas

	mol fr.
CCl ₃ NO ₂	0.02
air	0.98
	1.00

$$\frac{100 \text{ kPa}}{1 \text{ mol gas}} \left| \frac{0.02 \text{ mol } CCl_3NO_2}{101.3 \text{ kPa}} \right| \frac{760 \text{ mm Hg}}{101.3 \text{ kPa}} = 15.0 \text{ mm Hg}$$

(a) Using linear interpolation, which may introduce a slight error, 15.0 mm Hg corresponds to

$$\left(\frac{15.0 - 13.8}{18.3 - 13.8} \right) (5) = 1.3 + 15 = \boxed{16^\circ C} \quad (289.5K)$$

(a) Basis: 100 m³ at 100 kPa and 16.5°C

$$\frac{100 \text{ m}^3 \text{ air}}{101.3 \text{ kPa}} \left| \frac{100 \text{ kPa}}{289.5 K} \right| \frac{273 K}{289.5 K} \left| \frac{1 \text{ kg mol air}}{22.4 \text{ m}^3 \text{ air at SC}} \right|$$

(continued)

Solutions Chapter 17

$$\frac{0.02 \text{ mol CCl}_3\text{NO}_2}{0.98 \text{ mol air}} \left| \frac{164.5 \text{ kg CCl}_3\text{NO}_2}{1 \text{ kmol CCl}_3\text{NO}_2} \right| = \boxed{13.95 \text{ kg}}$$

17.5

Basis: 1 mol air

$$y = 0.12$$

$$p_{\text{H}_2\text{O}} = p_T(0.12) = 101.3 \text{ kPa}(0.12)$$

$$= 12.2 \text{ kPa}$$

The dewpoint is the temperature at which $p^*_{\text{H}_2\text{O}} = 12.2 \text{ kPa}$, or from the steam tables 323K or $\boxed{50^\circ\text{C}}$

17.6

Assume the tank with air fills with the hazardous liquid vapor at 80°F . The pressure in the tank with air will become after the transfer $(10 + 14.7) + 13 = \boxed{37.7 \text{ psia}}$ hence the seal will possibly rupture during the transfer

17.7

At 60°F , $p^*_{\text{H}_2\text{O}} = 0.52 \text{ in Hg}$; at 75°F , $p^* = 0.87 \text{ in Hg}$

Basis: 12,000 ft^3 air at 75°F and 29.7 in Hg absolute

$$\frac{12,000 \text{ ft}^3}{359 \text{ ft}^3 \text{ at SC}} \left| \frac{1 \text{ lb mol}}{29.92 \text{ in Hg total}} \right| \left| \frac{492^\circ\text{R}}{535^\circ\text{R}} \right| \left| \frac{18 \text{ lb H}_2\text{O}}{\text{lb mol}} \right| = \boxed{9.62 \text{ lb H}_2\text{O}}$$

Solutions Chapter 17

17.8

Basis: 1 gal benzene (sp. gr. 0.879, MW 78.1) at 750 mm Hg, 70°F

$$\text{Moles of air} = \frac{(3600 \text{ ft}^3)(750)(14.7)}{(10.73)(760)(530)} = 9.18 \text{ lb mol}$$

$$\text{Moles of benzene} = \frac{(1)(1 \text{ ft}^3)(0.879)(62.4)}{(7.48)(78)} = 0.094 \text{ mol}$$

$$n_{\text{Total}} = 9.18 + 0.094 = 9.274 \text{ mol}$$

$$y_{\text{Bz}} = \frac{0.094}{9.274} = 0.0101$$

mol % = $\boxed{1.01\%}$ therefore beneath explosive limit

17.9

Basis: 350 ft^3 $\text{C}_2\text{H}_2 - \text{O}_2$ mixture at 25°C , 745 mm Hg

$$n_1 = \frac{pV}{RT} = \frac{(745)(14.7)(350)}{(760)(10.73)(298)(1.8)} = 0.874 \text{ lb mol}$$

$$n_2 = \left(\frac{745}{760} \right) \left(\frac{14.7}{10.73} \right) \left(\frac{300}{333} \right) \left(\frac{1}{1.8} \right) = 0.671 \text{ lb mol}$$

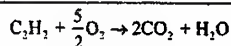
$$p^*_{\text{H}_2\text{O}} \text{ at } 60^\circ\text{C} = 149.4 \text{ mm Hg}$$

$$y_{\text{H}_2\text{O air}} = \frac{149.4}{745} = 0.201$$

$$n_{\text{H}_2\text{O}} = (0.201)(0.671) = 0.135 \text{ lb mol}$$

(continued)

Solutions Chapter 17



You get 1 mol H_2O /mol C_2H_2 on reaction

Therefore moles $\text{C}_2\text{H}_2 = 0.135$

mol $\text{O}_2 = 0.874 - 0.135 = 0.739$ lb mol

$$y_{\text{O}_2, \text{air}} = \frac{0.739}{0.874} = 0.845$$

$$V_{\text{O}_2} = (0.845)(350) = \boxed{296 \text{ ft}^3} \text{ at } 745 \text{ mm and } 25^\circ\text{C}$$

$$V_{\text{C}_2\text{H}_2} = 350 - 276 = \boxed{54 \text{ ft}^3} \text{ at } 745 \text{ mm and } 25^\circ\text{C}$$

17.10

Elephant seals have an average body temperature several degrees higher than ours. That means their breath can hold a bit more moisture than ours, and on that day, that extra moisture could have been just enough for condensation to occur.

But there are other reasons the elephant seals' breath may have been easier to see. It could be that it was a few degrees colder on the beach than where the observer was sited. And, as you know if you have ever experimented with seeing your breath, the bigger the volume of air, the more moisture available to condense out and so the condensed moisture was more visible.

17.11

(a) p_{Bz} exists if saturation occurs. Then, with $p_{\text{tot}} = 100 \text{ kPa}$

$$p_{\text{Bz}} = 100 (0.014) = 1.4 \text{ kPa which}$$

corresponds to

$$\boxed{-11^\circ\text{C}} \text{ from Perry}$$

Solutions Chapter 17

or use Antoine Eqn. and solve for T ($p_{\text{Bz}} = 10.5 \text{ mm Hg}$) (-15°C from the CD)

$$\ln(10.5) = 15.9008 - \frac{2788.51}{T - 52.36}$$

b) Repeat for $p_{\text{Bz}} = 8.0 \text{ kPa}$ (60 mm Hg) corresponding to $\boxed{15.4^\circ\text{C}}$

17.12

Basis: 1 lb air

If the air is saturated, $p_{\text{C}_8} = 2.36 \text{ in Hg}$ and $p_{\text{air}} = 29.66 - 2.36 = 27.30 \text{ in Hg}$.

$$\frac{p_{\text{C}_8}}{p_{\text{air}}} = \frac{2.36}{27.30} = 0.0864 \frac{\text{mol C}_8}{\text{mol air}}$$

$$(a) \frac{\text{lb air}}{\text{lb C}_8} = \frac{27.30 \text{ mol Air}}{2.36 \text{ mol C}_8} \left| \frac{29 \text{ lb air}}{1 \text{ lb mol air}} \right| \frac{1 \text{ lb mol C}_8}{114.2 \text{ lb C}_8} = \boxed{2.94 \frac{\text{lb air}}{\text{lb C}_8}}$$

$$(b) \frac{2.36 \text{ mol C}_8}{(27.30 + 2.36) \text{ mol total}} = \frac{n_{\text{C}_8}}{n_{\text{tot}}} = \boxed{0.080} \text{ which is also the fraction of the volume.}$$

$$(c) \frac{2.94 \text{ lb air}}{\text{lb C}_8} \left| \frac{1 \text{ lb mol air}}{29 \text{ lb air}} \right| \frac{359 \text{ ft}^3 \text{ at SC}}{1 \text{ lb mol air}} \left| \frac{580^\circ\text{R}}{492^\circ\text{R}} \right| \frac{29.92 \text{ in Hg}}{29.66 \text{ in Hg}}$$

$$= \boxed{43.3 \text{ ft}^3} \text{ at } 120^\circ\text{F and } 29.6 \text{ in. Hg/lb octane}$$

Solutions Chapter 17

17.13

At equilibrium, the pressure of Hg is its vapor pressure

$$\frac{p_{Hg}}{p_1} = \frac{n_{Hg}}{n_1} = \frac{p^*_{Hg}}{p_{air}} = \frac{1.729 \times 10^{-4} \text{ g mol Hg}}{99.5 \text{ g mol air}}$$

Note: $p_1 = p_{air} + p_{Hg} \approx p_{air}$ for all purposes so $\frac{1.729 \times 10^{-4} \text{ g mol Hg}}{99.5 \text{ g mol total gas}}$

Basis: $1.729 \times 10^{-4} \text{ g mol Hg}$

$$\frac{1.729 \times 10^{-4} \text{ g mol Hg}}{1 \text{ g mol Hg}} \left| \frac{200.59 \text{ g}}{1 \text{ g}} \right| \frac{1000 \text{ mg}}{1 \text{ g}} = 38.14 \text{ mg Hg}$$

$$V = \frac{nRT}{p}$$

$$\frac{99.5 \text{ g mol air}}{99.5 \text{ kPa}} \left| \frac{293.15 \text{ K}}{(kg \text{ mol})(K)} \right| \frac{8.314 \text{ (kPa)(m}^3\text{)}}{1000 \text{ g}} = 2.44 \text{ m}^3 \text{ at } 20^\circ\text{C and } 99.5 \text{ kPa}$$

$$15.65 \frac{\text{mg}}{\text{m}^3} \text{ at } 20^\circ\text{C and } 99.5 \text{ kPa.}$$

Level is not acceptable.

A mercury spill can be cleaned up reasonably effectively by dusting with sulfur, then vacuuming with a vacuum cleaner specifically designed for mercury pick-up, which prevents the escape of mercury vapor.

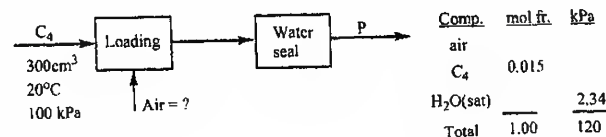
The instructor should point out to the student that the assumption of the "no ventilation" is not a very good approximation unless the surface of the mercury is rather large or there is truly no ventilation in the storeroom.

Solutions Chapter 17

17.14

Step 5: Basis: 1 min

Steps 2, 3, and 4: System is loading plus water seal, steady state, open



$$p^*_{H_2O} \text{ at } 20^\circ\text{C} = 2.34 \text{ kPa}$$

$$n_{C_4} = \frac{pV}{RT} = \frac{100.0 \text{ kPa}}{293.15 \text{ K}} \left| \frac{300 \text{ cm}^3}{100 \text{ cm}^3} \right| \left(\frac{1 \text{ m}}{100 \text{ cm}} \right)^3 \left| \frac{(\text{kg mol})(K)}{8.314 \text{ (kPa)(m}^3\text{)}} \right|$$

$$= 1.231 \times 10^{-5} \text{ kg mol} = 1.231 \times 10^{-2} \text{ g mol C}_4$$

Steps 6, 7, 8, and 9:

At P, the mole fraction of water is $2.34/120 = x_{H_2O} = 0.0195$

The moles of P come from a C₄ balance (C₄ is a tie element)

$$1.231 \times 10^{-2} = 0.015P \quad P = 0.821 \text{ g mol}$$

Then the air in is

$$0.821 (1 - 0.0195 - 0.015) = 0.793 \text{ g mol}$$

$$V = \frac{nRT}{p} = \frac{0.793 \times 10^{-3} \text{ kg mol}}{100 \text{ kPa}} \left| \frac{293.15 \text{ K}}{(\text{kg mol})(K)} \right| \frac{8.314 \text{ (kPa)(m}^3\text{)}}{1000 \text{ g}}$$

(continued)

Solutions Chapter 17

$$V = 1.93 \times 10^{-3} \text{ m}^3 \text{ at } 100.0 \text{ kPa and } 20^\circ\text{C per min}$$

17.15

Assume equilibrium.

At 75°F , from the Antoine equation, the vapor pressure of benzene is 90 mmHg. Assume the barometer is 760 mm Hg abs.

$$\frac{\text{mol Bz}}{\text{mol air}} = \frac{p_a^*}{p_t - p_a^*} = \frac{90}{760 - 90} = 0.13 \frac{\text{mol Bz}}{\text{mol air}}$$

- a) The OSHA limit is 1 ppm over 8 hours. The above greatly exceeds this limit.
- b) No, because the garage is probably not well ventilated, and also if a water heater is in the garage, the LEL (Lower Explosive Limit) may be exceeded.

17.16

Basis: 50 ft³ air at 29.92 in. Hg and 70°F

$$p_{\text{H}_2\text{O}}^* \text{ at } 50^\circ\text{F} = 0.36 \text{ in Hg}$$

The amount of water per hour is

$$\frac{50 \text{ ft}^3}{\text{min}} \left| \frac{60 \text{ min}}{1 \text{ hr}} \right| \left| \frac{1 \text{ lb mol}}{359 \text{ ft}^3} \right| \left| \frac{429^\circ\text{R}}{530^\circ\text{R}} \right| \left| \frac{0.36 \text{ in. Hg of H}_2\text{O}}{29.92 \text{ in. Hg total}} \right| \left| \frac{18 \text{ lb}}{\text{lb mol}} \right| = \frac{1.68 \text{ lb H}_2\text{O}}{\text{hr}}$$

Alternate solution: make air and water balances.

Solutions Chapter 17

17.17

Basis: 1 hr

The question really is: does the Hg condense at 150°F , or is it still a vapor (and thus not collected).

$$\text{The moles of Hg are: } 40,000 (0.023 \times 10^{-2}) \left| \frac{\text{lb Hg}}{200 \text{ lb Hg}} \right| \left| \frac{1 \text{ lb mol Hg}}{200 \text{ lb Hg}} \right| = 0.046 \text{ lb mol}$$

The moles of gas are (ignoring the Hg):

$$\frac{40,000 \text{ lb gas}}{32 \text{ lb gas}} \left| \frac{1 \text{ lb mol gas}}{32 \text{ lb gas}} \right| = 1250 \text{ lb mol}$$

$$y_{\text{Hg}} = \frac{0.046}{0.046 + 1250} = 3.68 \times 10^{-5}$$

The partial pressure of the Hg in the gas is $y_{p_{\text{total}}}$

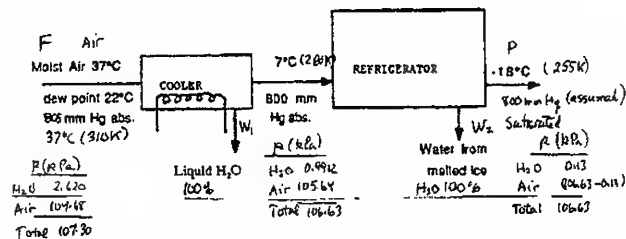
$$(3.68 \times 10^{-5})(14.7) = 5.4 \times 10^{-4} \text{ psia}$$

The Hg will remain a vapor and not condense.

Solutions Chapter 17

17.18

Basis: 20,000 ft³ moist air at entering conditions in 1 day



$$\frac{20,000 \text{ ft}^3}{280} \left| \frac{273}{760} \right| \left| \frac{800}{359 \text{ ft}^3 \text{ at SC}} \right| = 57.18 \text{ lb mol total}$$

(0.532 lb mol H₂O)

System: Refrigerator is system

Steps 6 and 7: Unknowns: W₂ and P; balance: H₂O and air

Steps 8 and 9:

$$\left. \begin{aligned} \text{H}_2\text{O}: 57.18 \left(\frac{0.9912}{106.63} \right) &= W_2(1) + P \left(\frac{0.13}{106.63} \right) \\ \text{Air}: 57.18 \left(\frac{105.64}{106.63} \right) &= W_2(0) + P \left(\frac{106.5}{106.63} \right) \text{ not accurate} \end{aligned} \right\} \begin{aligned} &\text{lb mol} \\ &P = 56.72 \\ &W_2 = 0.4613 \end{aligned}$$

$$\text{Total: } 57.18 = W_2 + P$$

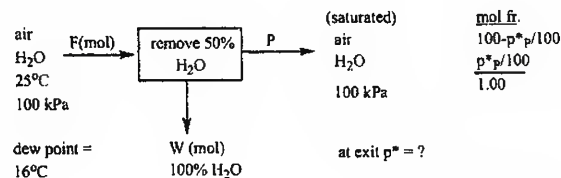
Basis: 30 days

$$30 (0.4613) (18) = \boxed{249 \text{ lb H}_2\text{O}/30 \text{ days}}$$

Solutions Chapter 17

17.19

Steps 1-4:



At 16°C

0.57 in Hg
0.28 psia

p*_{H₂O} ≈ 13.6 mm Hg = 1.81 kPa From steam tables p* = 1.92 kPa

Thus p_{air} = 100 - 1.81 = 98.18 kPa p_{air} = 100 - 1.92 = 98.08

Step 5: Basis is 100 Mol F

Step 6: Unknowns: W, P

Step 7: Balances: H₂O, air

Steps 8 & 9: Balances around process in mol

$$\boxed{\text{Air}} \quad 100 \left(\frac{98.08}{100} \right) = W(0) + P \left(\frac{100 - p^*_{\text{H}_2\text{O}}}{100} \right) \text{ in } P$$

$$\boxed{\text{H}_2\text{O}} \quad 100 \left(\frac{1.92}{100} \right) = W(1) + P \left(\frac{p^*_{\text{H}_2\text{O}} \text{ in } P}{100} \right)$$

$$\boxed{\text{Total}} \quad 100 = W + P$$

Also, p* = f(T) vapor pressure relation

(continued)

Solutions Chapter 17

- The exit gas has one-half the entering H_2O , or $\frac{1}{2}(1.92) = 0.96$ mol thus $W = \frac{1}{2}(1.92) = 0.96$ mol H_2O .
- The exit air has 98.08 mol dry air.
- At the exit $p_{\text{H}_2\text{O}} = p_{\text{H}_2\text{O}}^* = y_{\text{H}_2\text{O}}(100) = \frac{0.96}{0.96 + 98.08} 100 \approx 0.97$ kPa
- From the steam tables, this corresponds to about $\boxed{280 \text{ K}}$ $\boxed{(7^\circ\text{C})}$, or use Antoine Eq.

Note: Taking $\frac{1}{2}$ of $(1.92) = 0.96$ and dividing by 100 instead of $(p_{\text{H}_2\text{O}} + p_{\text{air}})$ is wrong. The answer is close to correct because of the very small amount of water.

17.20

Basis: 1000 m^3 sat. air at 99 kPa and 30°C

$$p_{\text{H}_2\text{O}}^* \text{ at } 30^\circ\text{C} = 0.6155 \text{ psia} = 31.8 \text{ mm Hg} = 4.24 \text{ kPa}$$

$$\frac{1000 \text{ m}^3}{22.415 \text{ m}^3 \text{ a tSC}} \left| \frac{1 \text{ kg mol}}{101.3 \text{ kPa}} \right| \left| \frac{99 \text{ kPa}}{303 \text{ K}} \right| \left| \frac{273 \text{ K}}{303 \text{ K}} \right| = 39.3 \text{ kg mol}$$

$$\text{or } n = \frac{99 \text{ kPa}}{303 \text{ K}} \left| \frac{1000 \text{ m}^3}{8.314 \text{ (kPa)(m}^3\text{)}} \right| \left| \frac{(\text{kg mol})(\text{K})}{303 \text{ K}} \right| = 39.3 \text{ kg mol}$$

Initial:

$$\text{Initial mol } \text{H}_2\text{O} = 39.3 \left(\frac{4.24}{99} \right) = 1.68 \text{ kg mol } \text{H}_2\text{O}$$

$$\text{Initial mol air} = 39.3 \left(\frac{99 - 4.24}{99} \right) = 39.3 - 1.68 = 37.62 \text{ kg mol air}$$

Final:

Solutions Chapter 17

At 14°C and 133 kPa, the air is still saturated, and $n_{\text{air}} = 37.62$ kg mol

$$p_{\text{H}_2\text{O}}^* \text{ at } 14^\circ\text{C} = 0.2302 \text{ psia} = 11.9 \text{ mm Hg} = 1.59 \text{ kPa} = p_{\text{H}_2\text{O}} \text{ @ } 14^\circ\text{C}$$

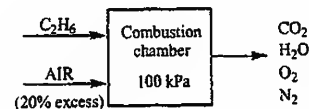
$$\frac{p_{\text{H}_2\text{O}}}{p_{\text{air}}} = \frac{n_{\text{H}_2\text{O}}}{n_{\text{air}}} \text{ so } \frac{1.59}{(133 - 1.59)} = \frac{n_{\text{H}_2\text{O}}}{37.62} \text{ There is the same as an } \text{H}_2\text{O} \text{ material balance}$$

$$n_{\text{H}_2\text{O}} = 0.46 \text{ kg mol}$$

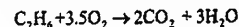
$$1.68 - 0.46 = 1.22 \text{ kg mol or } \boxed{22 \text{ kg}}$$

17.21

Steps 2, 3, and 4:



Assume combustion is complete and the gases are ideal. The process is open, steady state with reaction. The first objective is to make material balances.



Step 5: Basis: 100 mol C_2H_6

Step 4: The entering O_2 is 350 mol
 The excess O_2 is $(0.20)(3.50) = 70 \text{ mol}$
 Total O_2 is 420 mol
 The N_2 is $420 \left(\frac{0.79}{0.21} \right) = 1580 \text{ mol}$

Steps 6 and 7:

Unknowns: 4 (The components of the flue gas)

(continued)

Solutions Chapter 17

Balances: C, H, O, N, total of 4
Degrees of freedom = 0

Steps 8 and 9 (balances in moles, in = out):

$$\begin{array}{ll} \text{C:} & 2(100) = n_{\text{CO}_2} \quad n_{\text{CO}_2} = 200 \text{ mol} \\ 2\text{N:} & 1580 = n_{\text{N}_2} \quad n_{\text{N}_2} = 1580 \text{ mol} \\ \text{H:} & 6(100) = 2n_{\text{H}_2\text{O}} \quad n_{\text{H}_2\text{O}} = 300 \text{ mol} \\ \text{O:} & 420(2) = 2n_{\text{CO}_2} + n_{\text{H}_2\text{O}} + 2n_{\text{O}_2} \quad n_{\text{O}_2} = \underline{700 \text{ mol}} \\ & \text{Total} \quad \quad \quad 2150 \text{ mol} \end{array}$$

The dewpoint is the temperature at which the flue gas is saturated

$$p^*_{\text{H}_2\text{O}} = y_{\text{H}_2\text{O}} p_{\text{Total}} = \frac{300}{2150} (100 \text{ kPa}) = 14.0 \text{ kPa}$$

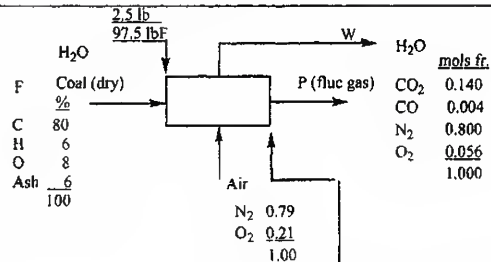
This pressure of H₂O corresponds (from the steam tables) to 325.7 K (52.6°C)

17.22

Step 5: Basis: 100 lb mol flue gas

Steps 2, 3, and 4:

Solutions Chapter 17



H₂O, dew point 50°F; $p^*_{\text{H}_2\text{O}} = 0.3624$ in flg

Steps 6 and 7:

Unknowns: F, A, W

Equations: Material balances: C, H, O (the ash is ignored)

Steps 8 and 9 (balances are in moles; in = out)

To get F:

$$\text{C: } (0.80F)(1/12) = (0.140 + 0.004) 100 \quad F = 216 \text{ lb or } 18.0 \text{ lb mol}$$

To get A:

$$\text{N}_2: 80 = A(0.79) \quad A = 101.27 \text{ lb mol}$$

H: Hydrogen from the dry coal plus the water in the coal is (MW H = 1.008):

$$\left[\frac{216(0.06)}{1.008} + \frac{2.5}{97.5} \left| \frac{216}{18.016} \right| \frac{2}{2} \right] \frac{1}{2} = 1 \quad 6.74 \text{ lb mol H}_2\text{O}$$

$$\text{In A: } p^*_{\text{H}_2\text{O}} = 0.3624 = y^*_{\text{H}_2\text{O}} p_{\text{total}} = y^*_{\text{H}_2\text{O}} (29.90)$$

$$y^*_{\text{H}_2\text{O}} = 0.0121$$

$$\text{The water in A is } (0.0121) (101.27) = \underline{1.23 \text{ lb mol}}$$

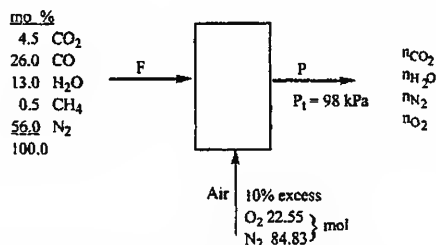
$$\text{Total H}_2\text{O in P: } W = 7.97 \text{ lb mol} \quad (\text{continued})$$

Solutions Chapter 17

The dew point is

$$\frac{7.97}{107.97} (29.92) = 2.21 \text{ in. Hg equivalent to } \boxed{105^\circ\text{F}}$$

17.23



Step 4: Calculate the xs air and add total air to the diagram

Step 5: Basis: 100 mol synthesis gas

Step 6: Unknowns: $n_{\text{O}_2}, n_{\text{CO}_2}, n_{\text{H}_2\text{O}}, n_{\text{N}_2}, P$ (5 total)

Step 7: Balances C, O, H, N, $\sum n_i = P$ (5 independent equations)

Steps 8, 9: Use element balances

	<u>In</u>		<u>out</u>	
C:	4.5	+	26.0 + 0.5	= n_{CO_2} $n_{\text{CO}_2} = 31.0$
H:	0.5 (4)	+	13 (2)	= $n_{\text{H}_2\text{O}}(2)$ $n_{\text{H}_2\text{O}} = \frac{28}{2}$

Solutions Chapter 17

$$\text{O}_2: \quad 4.5 \quad + \quad \frac{26.0}{2} + 22.55 = \quad n_{\text{CO}_2} + \frac{n_{\text{H}_2\text{O}}}{2} \quad n_{\text{O}_2} = 2.05$$

$$\text{N}_2: \quad 56.0 \quad + \quad 84.83 \quad = \quad n_{\text{N}_2} \quad n_{\text{N}_2} = \frac{140.8}{187.9}$$

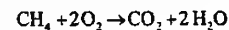
$$y_{\text{H}_2\text{O}} = \frac{28/2}{187.9} = \frac{14}{187.9}$$

$$p^*_{\text{H}_2\text{O}} = p_{\text{H}_2\text{O}} = 98 \left(\frac{14}{187.9} \right) = 7.3 \text{ kPa (or 1.06 psia)}$$

This is equivalent to a temperature of $\boxed{104^\circ\text{F}}$ from the steam tables (40°C)

17.24

Basis: 100 mol gases leaving absorber



$$\frac{0.8335 \text{ mol N}_2}{0.79 \text{ mol N}_2} \left| \frac{0.21 \text{ mol O}_2}{2 \text{ mol O}_2} \right| \frac{1 \text{ mol CO}_2}{2 \text{ mol O}_2} = 0.1108 \text{ mol CO}_2$$

$$1 - 0.8335 - 0.1108 = 0.0557 \text{ mol H}_2\text{O}; 0.00557 (20) = 1.114 \text{ psia}$$

Dew point $\approx \boxed{105^\circ\text{F}}$ at 1.114 psia

b) At constant temperature of 130°F , the gas must be compressed until the partial pressure increases and becomes equal to the vapor pressure in order to reach the point of condensation.

From Steam tables, the vapor pressure of water at 130°F is 2.223 psia.

The total pressure at which the partial pressure of water (mol fraction = 0.0557) will be 2.223 psia is

$$\frac{2.223}{0.0557} = \boxed{40.1 \text{ psia}}$$

$$p_{\text{H}_2\text{O}} = p_i y_{\text{H}_2\text{O}}$$

Solutions Chapter 17

17.25

Basis: 1 lb mol of benzene free air

$$\text{Barometric Pressure} = \frac{\text{mm Hg}}{742}$$

$$p^{\circ} \text{ benzene at } 40^{\circ}\text{C} = 181$$

$$\text{Partial pressure of air} = 561$$

$$\text{Partial pressure of benzene} = 181 \Rightarrow 0.323 \text{ lb mol benzene}$$

$$\text{At 25 psig total pressure or } 2052$$

$$p^{\circ} \text{ benzene at } 10^{\circ}\text{C} = 45.4$$

$$\text{Partial pressure of air } 2006.6$$

$$\text{Final partial pressure of benzene in air} = 45.4 \Rightarrow 0.023 \text{ lb mol benzene}$$

$$0.323 - 0.023 = 0.3 \text{ lb mol } \text{C}_6\text{H}_6 \text{ recovered}$$

$$a. \frac{(0.3)(100)}{(0.323)} = 92.9\% \text{ recovery}$$

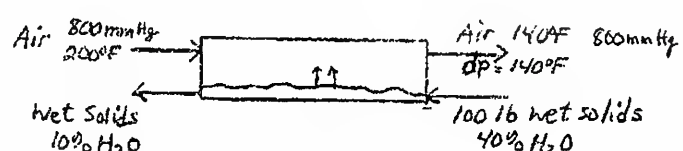
$$b. 2 \text{ psig is } 103 + 742 = 845 \text{ mm Hg}$$

$$\frac{(0.023)(845)}{(1.023)} = 18.9 \text{ mm Hg} \text{ partial pressure of benzene in the recycled air.}$$

Solutions Chapter 17

17.26

Steps 2, 3, and 4:

The dewpoint of 140°F gives $p'_{\text{H}_2\text{O}} = 149.3 \text{ mm Hg}$

Step 5:

Basis: 100 lb wet solids in (BDS is bone dry solids)

Steps 8 and 9:

BDS balance: 60 lb BDS = 0.90 (wet solids out)

wet solids out = 66.7 lb

From a total balance $100 - 66.7 = 33.3 \text{ lb H}_2\text{O evaporated} = 1.85 \text{ lb mol H}_2\text{O evaporated}$

For the air,

Assume the air exits at 1.0 atm

$$\text{Composition in: } \text{H}_2\text{O is } \frac{10}{800}(100) = 1.25\%$$

$$\text{Air is } \frac{790}{800}(100) = 98.75\%$$

$$\text{Composition out: } \text{H}_2\text{O is } \frac{149.3}{800}(100) = 18.7\% \text{ (continued)}$$

Solutions Chapter 17

$$\text{Air} = 81.3\%$$

Overall balance (mol) on the gas phase

$$A_{\text{in}} + 1.85 = A_{\text{out}}$$

Air balance (mol) on the gas phase

$$0.9875 A_{\text{in}} = 0.813 A_{\text{out}}$$

$$A_{\text{in}} = 8.619 \text{ lb moles wet air in}$$

$$\frac{8.619 \text{ lb mol}}{\text{lb mol}} \left| \frac{359 \text{ ft}^3}{492^\circ\text{R}} \right| \left| \frac{660^\circ\text{R}}{800} \right| \left| \frac{760}{800} \right| = \boxed{3940 \text{ ft}^3} \text{ of wet air @ 800 mm Hg and } 200^\circ\text{F}$$

(continued)

17.27

Basis: 1 hr

Calculate the amounts of the various components in the gas phase:

Water

$$\text{H}_2\text{O in} = 0 \text{ (by specification)}$$

$$\text{H}_2\text{O out (saturated):}$$

$$p^* \text{ at } 300 \text{ K} = 3.51 \text{ kPa} = p_{\text{H}_2\text{O}}$$

$$y_{\text{H}_2\text{O}} = \frac{3.51 \text{ kPa}}{110 \text{ kPa}} = 0.0319$$

CO₂

$$\text{CO}_2 \text{ in: } y_{\text{CO}_2} = 0.00055$$

$$\text{CO}_2 \text{ out: } y_{\text{CO}_2} = 0.125$$

Solutions Chapter 17

O₂

$$\text{O}_2 \text{ in: } y_{\text{O}_2} = 0.21$$

$$\text{O}_2 \text{ out: } y_{\text{O}_2} = 0.0804$$

Assume the other gas in and out is N₂.

The entering gas is

$$\frac{600 \text{ m}^3}{\text{m}^3} \left| \frac{120 \text{ kPa}}{300 \text{ K}} \right| \left| \frac{(\text{kg mol})(\text{K})}{8.314(\text{kPa})(\text{m}^3)} \right| = 28.87 \text{ kg mol}$$

The exit gas can be obtained from a N₂ balance

$$28.87(1 - 0 - 0.00055 - 0.21) = n_{\text{out}}(1 - 0.0319 - 0.125 - 0.0804)$$

$$n_{\text{out}} = 29.89 \text{ kg mol}$$

In one hour in the steady state the moles of CO₂ produced were

$$29.89(0.125) - 28.87(0.00055) = 3.72 \text{ kg mol}$$

The mole of O₂ consumed were

$$28.87(0.21) - 30.14(0.0804) = 3.64 \text{ kg mol}$$

$$\text{RQ} = \frac{3.72}{3.64} = \boxed{1.02}$$

Solutions Chapter 18

18.1

Basis: gas as given in problem statement

$$(a) 0.030 = \frac{p_{H_2O}}{p_{Tot} - p_{H_2O}} = \frac{p_{H_2O}}{101.6 - p_{H_2O}} \text{ so, } p_{H_2O} = 2.96 \text{ kPa}$$

$$p^*_{H_2O} \text{ at } 60^\circ\text{C} = 19.9 \text{ kPa}$$

$$\% \text{ humidity} = 100 \left(\frac{2.96}{19.9} \right) \left[\frac{101.6 - 19.9}{101.6 - 2.96} \right] = \boxed{12.2\%}$$

(b) Relative humidity

$$(100) \frac{2.96}{19.9} = \boxed{14.9\%}$$

(c) Dewpoint occurs where $p^*_{H_2O} = 2.96 \text{ kPa}$, or $T = \boxed{24^\circ\text{C}}$ from the steam tables.

18.2

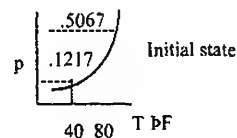
At 27°C , $p^*_{H_2O} = 3.52 \text{ kPa}$. The actual pressure of the water vapor is obtained from

$$p = \frac{nRT}{V} = \left(\frac{0.636}{18.01} \right) \left(\frac{8.314}{\text{J}} \right) \left(\frac{300 \text{ K}}{28.0} \right) = 3.15 \text{ kPa}$$

$$100 \left(\frac{3.15}{3.52} \right) = \boxed{89\% \text{ RH}}$$

Solutions Chapter 18

18.3

At 80°F , $p^*_{H_2O} = 0.5067 \text{ psia}$ from the steam tablesAt 40°F , $p^*_{H_2O} = 0.1217 \text{ psia}$ At 58°F , $p^*_{H_2O} = 0.2384 \text{ psia}$

$$(a) 100 \frac{0.1217 \text{ psia}}{0.5067 \text{ psia}} = \boxed{24\%}$$

(b) The mol fraction of H_2O vapor is constant on compression unless saturation is reached. At the initial conditions

$$y_{H_2O} = \frac{0.1217}{14.696} = 8.28 \times 10^{-3}$$

$$\text{At } 2 \text{ atm, } p_{H_2O} = p_{Tot} y_{H_2O} = (14.692)(2) \left(\frac{0.1217}{14.696} \right) = 0.2437 \text{ psia}$$

$$\frac{0.2437}{0.2384} > 1 \text{ hence water condenses and the}$$

relative humidity is 100%

Solutions Chapter 18

18.4

$$T = 140^{\circ}\text{F}$$

$$P_{\text{H}_2\text{O}}^* = 5.878 \text{ in Hg}$$

$$p = 30 \text{ in Hg}$$

$$H = 0.03 \text{ mol H}_2\text{O/mol BDA} \Rightarrow \text{Basis: 1 mol BDA}$$

$$\frac{\text{mol H}_2\text{O}}{\text{mol H}_2\text{O} + \text{BDA}} = \frac{0.03}{1 + .03} = 0.0291 = y_{\text{H}_2\text{O}}$$

$$p_{\text{H}_2\text{O}} = 30 (0.0291) = 0.874 \text{ in Hg}$$

$$p_{\text{air}} = 30 (1 - 0.0291) = 29.13 \text{ in Hg}$$

$$(a) \quad \% \text{ rel. humidity} = 100 \frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2\text{O}}^*} = 100 \left(\frac{0.874}{5.878} \right) = \boxed{14.9\%}$$

(b) Dew point is the temperature at which vapor first condenses on cooling at constant humidity, hence $p^* = 0.874 \text{ in Hg} \sim \boxed{75^{\circ}\text{F}}$.

18.5

From steam tables, $p_{\text{w}90^{\circ}\text{F}}^* = 0.6982 \text{ psia}$. Assume constant pressure during the process.

$$\text{Partial pressure of water, } p_{\text{w}} = (0.85) p_{\text{w}90^{\circ}\text{F}}^* = 0.593 \text{ psia}$$

$$\text{Partial pressure of dry air, } p_{\text{dry air}} = \text{Total pressure} - p_{\text{w}} = 14.696 - 0.593 = 14.103 \text{ psia}$$

(a) Molal humidity

Solutions Chapter 18

$$= \frac{\text{mol of water vapor}}{\text{mol of dry air}} = \frac{n_{\text{w}}}{n_{\text{dry air}}} = \frac{p_{\text{w}}}{p_{\text{dry air}}} = \frac{0.593}{14.013} = \boxed{0.042}$$

(b) Humidity

$$= \frac{\text{lb of water vapor}}{\text{lb of dry air}} = \frac{0.042 \text{ lb mol H}_2\text{O} | 18 \text{ lb H}_2\text{O/lb mol H}_2\text{O}}{\text{lb mol dry air} | 29 \text{ lb air/lb mol air}} = \boxed{0.026}$$

(c) Saturation temperature or the dew point is the temperature at which the vapor pressure of water will become equal to the existing partial pressure of 0.593 psia.

By interpolation dew point $\approx \boxed{84.8^{\circ}\text{F}}$

(d) Number of degrees of superheat

$$= 90^{\circ}\text{F} - 85^{\circ}\text{F} = \boxed{5^{\circ}\text{F}}$$

(e) At 105°F and 14.696 psia, all the water is still present as vapor, i.e., the gas phase composition and hence the partial pressures are unchanged from those at 90°F . The molal humidity and dew point are the same as at 90°F .

(f) At 60°F and 14.696 psia, the air is cooled below its original dew point of 85°C . Hence, water will condense, and the resulting air will be saturated with water vapor.

$$\therefore \text{The dew point} = \boxed{60^{\circ}\text{F}}$$

To find the molal humidity, find the partial pressures:

$$p_{\text{w}} = p_{\text{w}60^{\circ}\text{F}}^* = 0.2563 \text{ psi}$$

$$p_{\text{dry air}} = 14.696 - 0.256 \approx 14.44 \text{ psia}$$

Molar humidity

(continued)

Solutions Chapter 18

$$= \frac{n_w}{n_{\text{dry air}}} = \frac{p_w}{p_{\text{dry air}}} = \frac{0.2563}{14.44} = \boxed{0.0177 \text{ mol water / mol dry air}}$$

(g) Water condensed:

Basis: 1.0 mol of dry air

Initial water in air, at 90°F, 1 atm = $0.042 \frac{\text{mol water}}{\text{mol dry air}}$ Final water in air, at 60°F, 1 atm = $0.0177 \frac{\text{mol water}}{\text{mol dry air}}$ Water condensed = $0.042 - 0.0177 = 0.0243 \frac{\text{mol water}}{\text{mol dry air}}$ Fraction of the original water condensed = $\frac{0.0243}{0.042} = \boxed{0.58}$ Alternate solution:Make (1) a total balance, (2) an H₂O balance, (3) an air balance. Two are independent.

Use as a basis: 1 mole wet air

Solutions Chapter 18

18.6

T = 25°C, $p_{\text{Bz}} = 2.20 \text{ mm Hg}$, $p_t = 800 \text{ mm Hg}$, hence $p_{\text{air}} = 797.8 \text{ mm Hg}$

$$(a) \frac{n_{\text{Bz}}}{n_t} = \frac{p_{\text{Bz}}}{p_t} \therefore \frac{n_{\text{Bz}}}{n_t} = \frac{2.20}{800} = \boxed{2.75 \times 10^{-3} \text{ mol Bz / mol gas}}$$

$$(b) \frac{n_{\text{Bz}}}{n_t - n_{\text{B}}} = \frac{p_{\text{Bz}}}{p_t - p_{\text{B}}} \therefore \frac{n_{\text{Bz}}}{n_{\text{air}}} = \frac{2.20}{797.8} = \boxed{2.7576 \times 10^{-3} \text{ mol Bz / mol Bz free gas}}$$

$$(c) \frac{\text{g Bz}}{\text{g Bz free gas}} = \frac{2.7576 \times 10^{-3} \text{ mol Bz}}{1 \text{ mol air}} \left| \frac{78 \text{ g Bz}}{1 \text{ g mol Bz}} \right| \frac{1 \text{ g mol air}}{29 \text{ g air}} = \boxed{0.0074}$$

$$(d) \text{Relative Saturation} = \frac{p_{\text{Bz}}}{p^*_{\text{Bz at 25°C}}}$$

$$p^*_{\text{Bz at 25°C}} = 95.6 \text{ mm Hg} \therefore \text{Rel. Saturation} = \frac{2.20}{95.6} = \boxed{0.023}$$

$$(e) \frac{\mu\text{g Bz}}{\text{m}^3} = \frac{2.20 \text{ g mol Bz}}{800 \text{ g mol gas}} \left| \frac{78 \text{ g Bz}}{1 \text{ g mol Bz}} \right| \frac{10^6 \mu\text{g}}{1 \text{ g}} \left| \frac{1 \text{ g mol gas}}{22.4 \text{ L at STP}} \right|$$

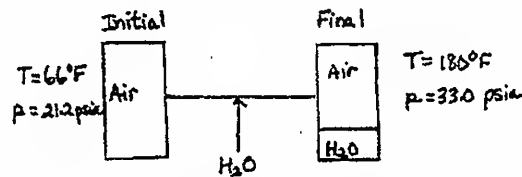
$$\left| \frac{1 \text{ L}}{1000 \text{ cm}^3} \right| \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^3 \left| \frac{760 \text{ mm Hg}}{800 \text{ mm Hg}} \right| \frac{298 \text{ K}}{273 \text{ K}} =$$

$$\boxed{9.96 \times 10^6 \text{ mg / m}^3 \text{ Exceeds the standard}}$$

$$(f) \frac{\text{g Bz}}{\text{ft}^3} = \frac{9.96 \times 10^6 \mu\text{g}}{\text{m}^3} \left| \frac{1 \text{ g}}{10^6 \mu\text{g}} \right| \frac{0.028 \text{ m}^3}{1 \text{ ft}^3} = \boxed{0.278 \text{ g Bz / ft}^3}$$

Solutions Chapter 18

18.7



Basis: Air at $T = 66^\circ\text{F}$ and 21.2 psia; assume V is constant.

(a) Initial

$$p_{\text{air},i} V = n_{\text{air}} RT_{66^\circ\text{F}}$$

Final

Assume all of the water evaporates, and check later on to see if the assumption is true.

$$p_{\text{air},f} + p_{\text{H}_2\text{O}} = p_f \text{ so } p_{\text{air},f} = p_f - p_{\text{H}_2\text{O}}$$

$$p_{\text{air},f} V = n_{\text{air}} RT_{180^\circ\text{F}}$$

The material balance is simple: all the initial air = final air.

$$\frac{p_{\text{air},i}}{p_i - p_{\text{H}_2\text{O}}} = \frac{66 + 460}{180 + 460} = \frac{526}{640} = \frac{21.2}{33.0 - p_{\text{H}_2\text{O}}}$$

$$p_{\text{H}_2\text{O}} = 7.20 \text{ psia}$$

Since $p^* = 7.51$ psia, all of the water can evaporate and the air will not be saturated.

(b) Basis: 1 lb H_2O (0.0555 lb mol H_2O)

At the final condition

Solutions Chapter 18

$$\frac{p_{\text{H}_2\text{O}}}{p_i} = \frac{7.20}{33.0} = \frac{n_{\text{H}_2\text{O}}}{n_i} = \frac{0.0555}{n_i} \text{ so } n = 0.254 \text{ lb mol}$$

$$V = \frac{nRT}{p} = \left(\frac{0.254}{33.0} \right) \left(\frac{10.73}{33.0} \right) \left(\frac{640}{33.0} \right) = \boxed{53.0 \text{ ft}^3}$$

$$(c) n_{\text{air}} = 0.254 - 0.0555 = 0.1985 \text{ lb mol} \quad \frac{1 \text{ lb H}_2\text{O}}{0.1985(29)} = \boxed{\frac{0.17 \text{ lb H}_2\text{O}}{\text{lb air}}}$$

18.8

The vapor pressure of ethyl acetate at 30°C is 122.5 mm Hg.

$$\% \text{ relative saturation} = 50 = \frac{p_{\text{EtAc}}}{p_{\text{EtAc}}^*} (100)$$

$$p_{\text{EtAc}} = 0.50 (122.5) = 61.2 \text{ mm Hg}$$

Basis: 740 mol EA

$$(a) \frac{n_{\text{EtAc}}}{n_i} = \frac{p_{\text{EtAc}}}{p_i} = \frac{61.2}{740} = 0.0828$$

Hence the vapor analyzes $\boxed{8.28\% \text{ EtAc and } 91.72\% \text{ air}}$

(b) Molal saturation is

$$\frac{n_{\text{EtAc}}}{n_{\text{air}}} = \frac{p_{\text{EtAc}}}{p_{\text{air}}} = \frac{p_{\text{EtAc}}}{p_t - p_{\text{EtAc}}} = \frac{61.2}{740 - 61.2} = \boxed{0.090 \frac{\text{mol EtAc}}{\text{mol air}}}$$

Solutions Chapter 18

18.9

Basis: 0.0083 lb mol H₂O vapor/lb mol CH₄

(a) $p_{\text{H}_2\text{O}}^*$ at 80°F = 26 mm Hg (steam tables)

$$p_{\text{H}_2\text{O}}/p_{\text{total}} = n_{\text{H}_2\text{O}}/n_{\text{total}}$$

$$y_{\text{H}_2\text{O}} = \frac{0.0083}{1.0083}$$

$$y_{\text{H}_2\text{O}} p_{\text{total}} = p_{\text{H}_2\text{O}}$$

$$\frac{0.0083}{1.0083} \frac{1520}{1} = 12.5 \text{ mm Hg} = p_{\text{H}_2\text{O}}$$

$$\frac{12.5}{26} = \boxed{0.48}$$

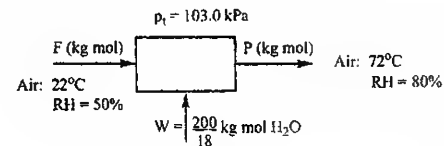
(b) $\frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2\text{O}}^*} = \frac{12.5}{62.5} = 0.20$

When $p_{\text{H}_2\text{O}}^* = 62.5 \text{ mm Hg}$, the temperature is $\boxed{109^\circ\text{F}}$

Solutions Chapter 18

18.10

Steps 1, 2, 3, and 4:



	$T (^{\circ}\text{C})$	$p^* (\text{kPa})$
Data for p^*		
from the steam tables:	22°C (295K)	2.622
	72°C (345K)	33.77

These calculations provide the composition of F and P.

In		kPa		Out		kPa
$p_{\text{H}_2\text{O}} = 0.50 (2.60)$	=	1.31		$p_{\text{H}_2\text{O}} = 0.80 (33.77)$	=	27.02
$p_{\text{air}} = 103.0 - 1.31$	=	101.69	p_{air}	$= 102.0 - 27.0$	=	76.0
p_t	=	103.0		p_t	=	103.0

Step 5: Basis: $W = 200 \text{ kg H}_2\text{O} (1 \text{ hour})$

Steps 6 and 7: Unknowns are: F, P Balances are: H₂O, air

Steps 8 and 9: This is a steady state process without a reaction

(continued)

Solutions Chapter 18

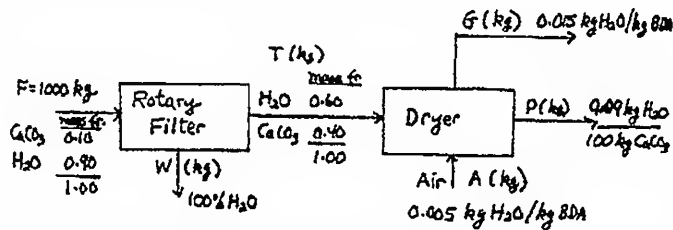
Balances	In	Out
H ₂ O	$F(1.3\%) + 200\% (1.00) = P(27.9\%)$	
air:	$F(101\%)$	$= P(79\%)$
F = 32.86 kg mol		P = 43.95 kg mol
Bone dry air:	$F(1.07\%) = 32.45 \text{ kg mol}$	$P(7\%) = 32.43 \text{ kg mol}$

Step 10: Check using total balance

Weight in kg of dry air used = 32.45 (29 = 941 kg)

18.11

Steps 1, 2, 3, and 4: This is a steady state process without reaction.



Calculate the composition of G, P, A in terms of mass fractions

Solutions Chapter 18

		mass fr.
G	0.015 kg H ₂ O	0.01477
	<u>1.000 kg air</u>	<u>0.98523</u>
	1.015 kg total	1.00000
P	9.09 kg H ₂ O	0.08339
	<u>100.00 kg CaCO₃</u>	<u>0.91661</u>
	109.00 kg total	1.00000
A	0.005 kg H ₂ O	0.004975
	<u>1.000 kg air</u>	<u>0.995025</u>
	1.005 kg to total	1.00000

Step 5: System is the filter. Basis: F = 1000 kg

Step 6: Unknowns: T, W

Steps 7, 8, and 9:

	In		Out
CaCO ₃ balance:	1000 (0.10)	=	T (0.40)
H ₂ O	1000 (0.90)	=	T (0.60) + W (1.00)
Total	1000	=	T + W

The balances are not independent; only 2 are independent.

All we need is the CaCO₃ balance as CaCO₃ is a tie component.

- a. T = 250 kg
W = 1000 - 250 = 750 kg

b. System is the dryer; same basis.

(continued)

Solutions Chapter 18

Step 6: The unknowns are G, P, and A

Steps 7, 8, and 9: We have 3 balances: H_2O , air, $CaCO_3$

	In			Out
$CaCO_3$:	250 (.40)	=		P (100/109.09)
				P = 109.09 kg

(From an overall system balance on $CaCO_3$ with 100 kg $CaCO_3$ in and out in P the water out in P = 9.09 kg.)

$$\text{air: } A \left(\frac{1.000}{1.005} \right) = G \left(\frac{1.000}{1.015} \right)$$

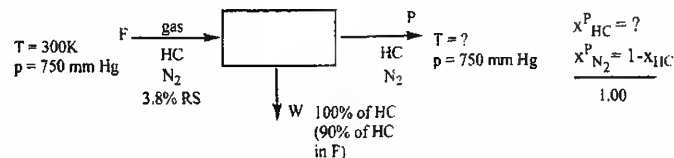
$$H_2O: 250(.60) + A \left(\frac{0.005}{1.005} \right) = G \left(\frac{0.015}{1.015} \right) + P \left(\frac{9.09}{109.09} \right)$$

$$\boxed{A = 14,400 \text{ kg}}$$

18.12

Step 5: Basis: 1 mol F

Steps 2, 3, and 4:



Solutions Chapter 18

$$\ln p_{300}^* = 15.9008 - \frac{2788.51}{300 - 52.36}$$

$$p_{300}^* = 103.6 \text{ mm Hg}$$

$$p_{HC} = 103.6(0.038) = 3.94$$

$$p_{N_2} = 746.06$$

$$p_T = 750.0$$

Steps 6 and 7:

Unknowns: W, P, x_{HC}^P

Balances: HC, N_2 , 90% of HC in W

Steps 8 and 9:

Total balance: $1 = W + P$

$$\text{HC balance: } 1 \left(\frac{3.94}{750} \right) = W(1.0) + P x_{HC}^P$$

$$1 \left(\frac{3.94}{750} \right) 0.90 = W = 0.00473$$

$$p = 1 - 0.00473 = 0.99527 \text{ mol}$$

$$x_{HC}^P = \frac{\left(\frac{3.94}{750} \right) (0.1)}{0.99527} = 0.00053 \quad p_{HC} = p_T (0.00053)$$

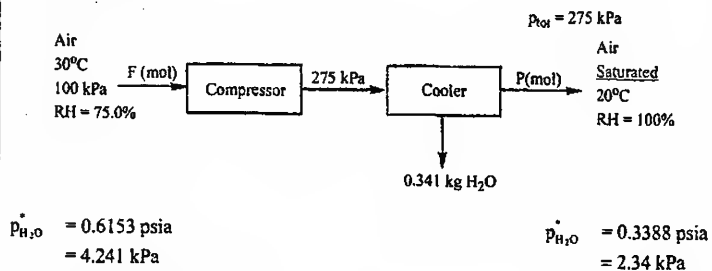
$$p_{HC} = 0.00053(750) = 0.396 \text{ mm Hg} = p_{HC}^*$$

$$\ln (0.396) = 15.9008 - \frac{2788.51}{T - 52.36} \quad \boxed{T = 218 \text{ K}}$$

Solutions Chapter 18

18.13

Steps 1, 2, 3, and 4:



System: overall

Step 5: Basis: 0.341 kg H₂O (0.341/18) kg mol

Step 6 and 7: Unknowns: F, P Balances: air, H₂O

Steps 8 and 9: Balances are in kg mol

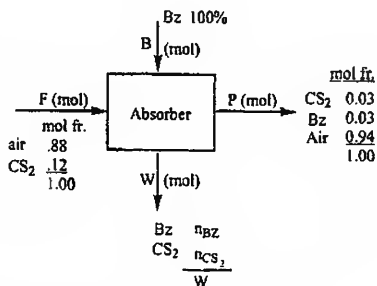
$$\begin{aligned}
 \text{Total: } F &= P + \frac{0.341}{18} \\
 \text{Air: } F \left(\frac{100 - 3.18}{100} \right) &= P \left(\frac{275 - 2.34}{275} \right) \\
 \text{H}_2\text{O: } F \left(\frac{3.18}{100} \right) &= \frac{0.341}{18} + P \left(\frac{2.34}{275} \right)
 \end{aligned}
 \left. \vphantom{\begin{aligned} \text{Total: } F \\ \text{Air: } F \\ \text{H}_2\text{O: } F \end{aligned}} \right\} \begin{array}{l} \text{Solve any two to get} \\ F = 0.804 \text{ kg mol} \end{array}$$

Solutions Chapter 18

$$V = \frac{0.804 \text{ kg mol}}{100} \left| \frac{8.314}{303} \right| = 20.3 \text{ m}^3 \text{ at } 30^\circ\text{C and } 100 \text{ kPa}$$

18.14

Steps 1, 2, 3, and 4:



Step 5: Basis: P = 100 mol

Steps 6 and 7: Unknowns are F, B, n_{Bz} , n_{CS_2}

Balances are CS₂, Bz, Air

Steps 8 and 9:

$$\begin{aligned}
 \text{CS}_2: \quad F(0.12) &= n_{\text{CS}_2} + 100(0.03) \\
 \text{Bz:} \quad B &= n_{\text{Bz}} + 100(0.03) \\
 \text{Air:} \quad F(0.88) &= 100(0.94) \\
 F = 106.8 \text{ mol} \quad n_{\text{CS}_2} &= 9.82 \text{ mol}
 \end{aligned}$$

(continued)

Solutions Chapter 18

$$\text{Fraction CS}_2 \text{ recovered} = \frac{9.82}{12.82} = \boxed{0.77}$$

18.15

Pick a closed system in which the octane lost to the surroundings is part of the system rather than an open system.

During the day, the vapor space is saturated and expands so that the air-hydrocarbon mixture escapes through the vent. At night, the gas mixture contracts, and fresh air enters so that more liquid will vaporize.

The volume change of the mixture due just to the temperature change (assume p_{total} is constant) is

$$\frac{dV_v}{V_0} = \frac{dT}{T} \quad \text{using the ideal gas law}$$

where V_0 is the volume of the free space. As T increases, the vapor pressure of the octane increases and the number of moles of octane increases. The volume change due to the vaporization is

$$\frac{dV_v}{V_0} = dy = d \frac{n_{\text{octane}}}{n_{\text{air}}} \frac{dp^*}{p_1}$$

where y is the mole fraction of octane in the vapor space, p^* is the vapor pressure of the octane, and p_1 is the total pressure in the vapor space.

Thus, the total volume change is approximately

$$\frac{dV}{V_0} = \left(\frac{dT}{T} + \frac{dp^*}{p_1} \right)$$

Introduce $pV = nRT$ to get

Solutions Chapter 18

$$dn = \frac{V_0 p^* dT}{RT^2} + \frac{V_0 p^* dp^*}{pRT}$$

Introduce the equation

$$\ln(p^*) = A - \frac{B}{T}$$

to get

$$dn = \frac{V_0 e^{[A - (B/T)]} dT}{RT^2} + \frac{V_0 p dp^* [A - \ln p^*] dp^*}{RB p_1}$$

Integrate between T_1 and T_2 to get N , the octane in lost in a day

$$N = \left(\frac{V_0}{RB} \right) \left\{ \exp[A - (B/T_2)] - \exp[A - (B/T_1)] \right\} + \frac{A}{2p_1} \left[p_2^* - p_1^* \right] - \frac{1}{p_1} \left[p_2^* \frac{\ln p_1^*}{2} - \frac{1}{4} \right] - p_1^* \left(\frac{\ln p_1^*}{2} - \frac{1}{4} \right)$$

For octane $p_1 = 44$ mm Hg abs, $p_2 = 222$ mm Hg.

$$A = 7.30, \quad B = 1,600$$

$$\text{If } V_0 = 1 \text{ m}^3, \quad \boxed{N = 3.40 \text{ mol for 1 day.}}$$

18.16

(a)

Entering

Leaving

80°F = 26.8°C

70°F = 21.0°C

(continued)

Solutions Chapter 18

$$p^* \text{ at } 26.8^\circ\text{C} = 26 \text{ mm Hg}$$

$$\text{Rel. Humidity} = \frac{p}{p^*} = \frac{5 \text{ mm Hg}}{26 \text{ mm Hg}} (100)$$

$$= 19.2\%$$

(b) Entering

$$\text{Vol fr.} = \frac{V}{V_{\text{tot}}} = \frac{p}{p_{\text{tot}}}$$

$$\text{H}_2\text{O}: \frac{5 \text{ mm Hg}}{740 \text{ mm Hg}} (100) = 0.676\%$$

$$\text{Air}: 100 - 0.676 = 99.324\%$$

(c) EnteringBasis: 1 lb mol at 80°F , 740 mm Hg
Vol % = mol %

	lb	wt %
H ₂ O: (0.00676)(18)	0.12	0.4
Air: (99.324)(29)	28.80	99.6
	28.92	100.0

(d) EnteringBasis: 1 lb mol at 80°F , 740 mm HgActual: $p_{\text{vap}} = 5 \text{ mm Hg}$

$$p^* \text{ at } 21.0^\circ\text{C} = 19 \text{ mm Hg}$$

$$\text{Rel. Humidity} = \frac{p}{p^*} = \frac{18 \text{ mm Hg}}{19 \text{ mm Hg}} (100)$$

$$= 94.8\%$$

Leaving

$$\text{Vol fr.} = \frac{p}{p_{\text{tot}}}$$

$$\text{H}_2\text{O}: \frac{18 \text{ mm Hg}}{740 \text{ mm Hg}} (100) = 2.43\%$$

$$\text{Air}: 100 - 2.43 = 97.57\%$$

LeavingBasis: 1 lb mol at 70°F , 740 mm Hg

	lb	wt %
H ₂ O: (0.0243)(18)	0.44	1.53
Air: (0.9757)(29)	28.30	98.47
	28.74	100.00

LeavingBasis: 1 lb mol at 70°F , 740 mm HgActual: $p_{\text{vap}} = 18 \text{ mm Hg}$

Solutions Chapter 18

$$p_{\text{vapor-free gas}} = 740 - 5 = 735 \text{ mm Hg}$$

$$p_{\text{vapor-free air}} = 740 - 18 = 722 \text{ mm Hg}$$

$$\text{Humidity} = \frac{\text{g mol H}_2\text{O}}{\text{g mol dry air}} \left| \frac{18 \text{ g}}{1 \text{ g mol H}_2\text{O}} \right| \left| \frac{1 \text{ g mol dry air}}{29 \text{ g}} \right|$$

$$\frac{n_{\text{H}_2\text{O}}}{n_{\text{dry air}}} = \frac{p_{\text{H}_2\text{O}}}{p_{\text{dry air}}}$$

EnteringLeaving

$$\text{Humidity} = \frac{5}{735} \left| \frac{18}{29} \right| = 4.22 \times 10^{-3} \frac{\text{g H}_2\text{O}}{\text{g dry air}} \quad \frac{18}{722} \left| \frac{18}{29} \right| = 0.0155 \frac{\text{g H}_2\text{O}}{\text{g dry air}}$$

(e) Basis: 1000 ft³ of mixture at 740 mm Hg and TEnteringLeaving

$$\text{Vol \% H}_2\text{O} = 0.676 \%$$

$$\text{Vol \% H}_2\text{O} = 2.43 \%$$

$$\text{Vol H}_2\text{O} = (0.00676)(1000 \text{ ft}^3) = 6.76 \text{ ft}^3 \quad \text{Vol H}_2\text{O} = (0.0243)(1000 \text{ ft}^3) = 24.3 \text{ ft}^3$$

@ 26.8°C and 740 mm Hg@ 21.0°C and 740 mm Hg

$$\frac{6.76 \text{ ft}^3}{1 \text{ lb mol}} \left| \frac{1 \text{ lb mol}}{359 \text{ ft}^3} \right| \left| \frac{492^\circ\text{R}}{540^\circ\text{R}} \right| \left| \frac{740 \text{ mm Hg}}{760 \text{ mm Hg}} \right| \left| \frac{18 \text{ lb}}{1 \text{ lb mol}} \right|$$

$$\frac{24.3 \text{ ft}^3}{1 \text{ lb mol}} \left| \frac{1 \text{ lb mol}}{359 \text{ ft}^3} \right| \left| \frac{740 \text{ mm Hg}}{760 \text{ mm Hg}} \right| \left| \frac{492^\circ\text{R}}{530^\circ\text{R}} \right| \left| \frac{18 \text{ lb}}{1 \text{ lb mol}} \right|$$

$$= 0.30 \text{ lb H}_2\text{O} / 1000 \text{ ft}^3 \text{ at } 80^\circ\text{F and } 740 \text{ mm Hg}$$

$$= 1.10 \text{ lb H}_2\text{O} / 1000 \text{ ft}^3 \text{ at } 70^\circ\text{F and } 740 \text{ mm Hg}$$

(f) EnteringLeaving

$$\frac{0.30}{0.99324}$$

$$\frac{1.10}{0.9757}$$

(continued)

Solutions Chapter 18

$$= 0.302 \text{ lb H}_2\text{O} / 1000 \text{ ft}^3 \text{ vapor free air}$$

$$= 1.127 \text{ lb H}_2\text{O} / 1000 \text{ ft}^3 \text{ vapor free air}$$

(g) Basis: 800,000 ft³/day at 80°F, 740 mm Hg

Entering

Leaving

$$\text{Vol \% air} = 99.324 \%$$

$$\text{Vol dry air} = 794,600 \left(\frac{530}{540} \right)$$

$$\text{Vol dry air} = (800,000)(0.99324)$$

$$= 779,900 \text{ ft}^3 \text{ at } 70^\circ\text{F}$$

$$= 794,600 \text{ ft}^3$$

$$\text{Vol \%} = 97.57 \%$$

$$\text{Vol H}_2\text{O vapor} = (800,000)(0.00676)$$

$$\text{Total vol} = \frac{779,900}{0.9757} = 799,300 \text{ ft}^3$$

$$= 5400 \text{ ft}^3 \text{ at } 80^\circ\text{F}, 740 \text{ mm Hg}$$

$$\text{Vol H}_2\text{O vap} = 799,300 - 779,900$$

$$5400 \text{ ft}^3 \left(\frac{740}{760} \right) \left(\frac{492}{540} \right)$$

$$= 19,400 \text{ ft}^3 \text{ at } 70^\circ\text{F}, 740 \text{ mm Hg}$$

$$= 4790 \text{ ft}^3 \text{ at SC}$$

$$19,400 \left(\frac{492}{530} \right) \left(\frac{740}{760} \right) = 17,535 \text{ at SC}$$

$$\text{Water evaporated} = 17,535 - 4,790 = 12,745 \text{ ft}^3 \text{ at SC}$$

$$\frac{12,745 \text{ ft}^3}{359 \text{ ft}^3} \left| \frac{1 \text{ lb mol}}{18 \text{ lb}} \right| = 639 \text{ lb H}_2\text{O/day}$$

Part g could also be worked using part f and the volume of dry air:

Entering

Leaving

$$794,600 \text{ ft}^3 \text{ dry air}$$

$$779,900 \text{ ft}^3 \text{ dry air}$$

Solutions Chapter 18

$$0.302 \text{ lb H}_2\text{O}/1000 \text{ ft}^3 \text{ dry air (see f)}$$

$$1.127 \text{ lb H}_2\text{O}/1000 \text{ ft}^3 \text{ dry air (see f)}$$

$$\frac{794,600}{1000} \left| \frac{0.302}{1000} \right| = 240 \text{ lb H}_2\text{O}$$

$$\frac{779,900}{1000} \left| \frac{1.127}{1000} \right| = 879 \text{ lb H}_2\text{O}$$

$$\text{Water evaporated} = 879 - 240 = 639 \text{ lb H}_2\text{O / day}$$

18.17

$$p_{\text{H}_2\text{O}} \text{ at } 70^\circ\text{F} = 19.0 \text{ mm Hg}$$

$$p_{\text{H}_2\text{O}}^* \text{ at } 140^\circ\text{F} = 149.4 \text{ mm Hg}$$

$$p_{\text{H}_2\text{O}} \text{ at } 70^\circ\text{F} = (19.0)(0.50) = 9.5 \text{ mm Hg}$$

$$p_{\text{H}_2\text{O}} \text{ at } 140^\circ\text{F} = (149.4)(0.80) = 119.4 \text{ mm Hg}$$

$$\text{Basis: } 760 \text{ mol wet air in, or use } 200 \text{ lb H}_2\text{O entering}$$

$$\text{Balances: Air: } \left(\frac{750.5}{760} \right) F = \left(\frac{640.5}{760} \right) P$$

$$\text{H}_2\text{O: } \left(\frac{9.5}{760} \right) F + \left(\frac{200}{18} \right) = \left(\frac{119.4}{760} \right) P$$

$$\text{or: } \frac{119.4 \text{ mol H}_2\text{O out}}{640.6 \text{ mol BDA out}} \left| \frac{750.5 \text{ mol BDA in}}{760 \text{ mol W.A. in}} \right| = \frac{140 \text{ mol H}_2\text{O out}}{760 \text{ mol W.A. in}}$$

$$140 - 9.5 = 130.5 \frac{\text{mol H}_2\text{O evap.}}{760 \text{ mol W.A. in}}$$

$$\frac{760 \text{ mol W.A. in}}{130.5 \text{ mol H}_2\text{O}} \left| \frac{750.5}{760.0} \right| \left| \frac{200 \text{ lb H}_2\text{O}}{\text{hr}} \right| \left| \frac{\text{lb mol}}{18 \text{ lb}} \right| \left| \frac{359 \text{ ft}^3}{\text{lb mol}} \right| \left| \frac{530}{492} \right| = 24,700 \frac{\text{ft}^3}{\text{hr}} \text{ BDA in}$$

Solutions Chapter 18

18.18

Basis: 1000 ft³ wet air at 30°C and 740 mm Hg

$$p_{H_2O} = 1.253 \text{ in Hg} \\ = 31.9 \text{ mm Hg}$$

$$p_{air} = 740 - 31.9 = 708.1 \text{ mm Hg}$$

$$(a) \frac{1000 \left[\frac{31.8}{740} \right] \left[\frac{740}{760} \right] \left[\frac{273}{359} \right] \left[\frac{18}{2} \right]}{1} = 0.946 \text{ lb } H_2O$$

$$(b) \frac{1000 \left[\frac{740 - 31.8}{740} \right]}{1} = 958 \text{ ft}^3 \text{ dry air at 740 mm Hg and } 30^\circ\text{C}$$

or 1000 ft³ at 708.1 mm Hg and 30 °C

18.19

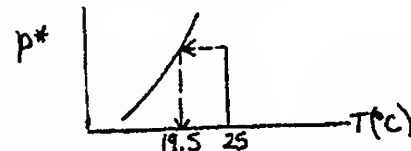
$$p^*_{25^\circ\text{C}} = 23.8 \text{ mm Hg (3.17 kPa)}$$

$$p^*_{19.5^\circ\text{C}} = 17.0 \text{ mm Hg (2.27 kPa)}$$

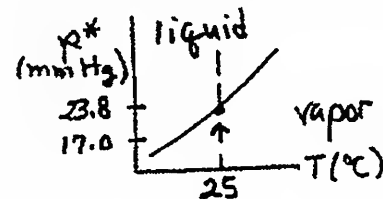
Assume a constant total pressure process for (1).

(1) At 100 kPa, p_{H_2O} is constant and the saturation temperature is the temperature at which the water vapor starts to condense, namely 19.5°C.

Solutions Chapter 18

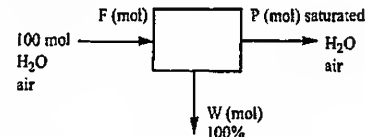


(2) At 25°C, compression increases p^* (volume changes), but y_{H_2O} is constant.



$$p_{H_2O} = p_{tot} y_{H_2O} \text{ so that } \frac{p_{tot,2}}{p_{tot,1}} = \frac{(p_{H_2O})_2}{(p_{H_2O})_1} = \frac{p^*_{25^\circ\text{C}}}{p^*_{19.5^\circ\text{C}}}$$

$$p_{tot,2} = 100 \text{ kPa} \left(\frac{23.8}{17.0} \right) = 140 \text{ kPa}$$



(3) Basis: 100 mol wet vapor

$$p^*_{(H_2O)_2} = p y_{(H_2O)_2} \quad (\text{continued})$$

Solutions Chapter 18

$$\frac{n_{\text{H}_2\text{O}}}{n_{\text{tot}}} = \frac{p_{\text{H}_2\text{O}}}{p_{\text{tot}}} = y_{\text{H}_2\text{O}}$$

Exit composition

		mol fr.
Air	97.73	0.99795
H ₂ O	0.908	0.009205
	98.683	1.0000

The material balances:

Initial
mol or kPa

Final

Air: $100 - 2.27 = 97.73$

To remove 60% of water vapor (40% is left):

H₂O: $2.27 = \frac{2.27}{100.00}$

$n_2 = 0.4 (2.27) = 0.908 \text{ mol}$

All of the air is left, $n_{\text{Air}} = 97.73$

$$p^*_{\text{H}_2\text{O}} = 100 \left(\frac{0.908}{97.73 + 0.908} \right) = 0.9205 \text{ kPa}$$

(6.906 mm Hg)

(a) 6.91 mm Hg corresponds to $\boxed{6.22^\circ\text{C}}$

(b) At constant temperature, the pressure increases until

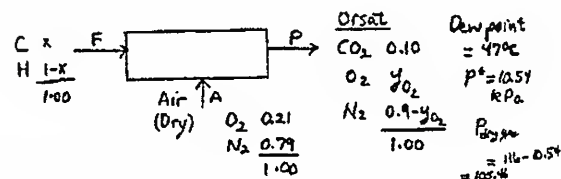
$y_{(\text{H}_2\text{O})_2} = 0.9205/100 = 0.009205$ (saturation at 25°C and p_1)

(b) $p^*_{25^\circ\text{C}} = p_1, y_{(\text{H}_2\text{O})_2} \quad p_1 = \frac{3.17 \text{ kPa}}{0.009205} = \boxed{344 \text{ kPa}}$

(c) Process (1) is probably more economical because the 344 kPa requires higher cost equipment.

Solutions Chapter 18

18.20



Basis: 1 mol P

Unknowns: x, F, A, y_{O₂}, WBalances: C, H, O, N plus dew point for H₂O is given so mol fraction H₂O is known

All balances are in moles.

C: $Fx = P(0.10) \quad \frac{W}{P} = \frac{10.54}{105.46}$

H: $F(1-x) = W(2)$

N₂: $A(0.79) = P(0.9 - y_{\text{O}_2})$

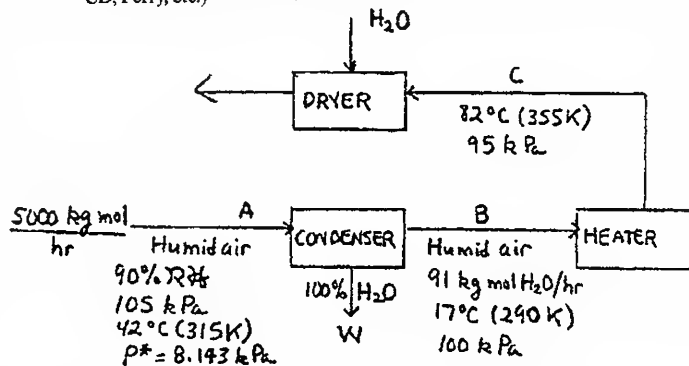
O₂: $A(0.21) = P(0.10 + y_{\text{O}_2}) + \frac{W}{2}$

$$x = 0.33 \quad \frac{1-x}{x} = \frac{H}{C} = \frac{0.667}{0.333} = \boxed{2.00}$$

Solutions Chapter 18

18.21

Note: This problem will give different results depending on the source of the vapor pressure data (steam tables, Antoine Eq., CD, Perry, etc.)



(steam tables $p^* = 8.214$; paper steam tables $p^* = 8.143$; CD $p^* = 8.181$)

Basis: 5000 kg mol air

$$RH = \frac{p_{H_2O}(100)}{p_{H_2O}} ; 90 = \frac{p_{H_2O}(100)}{8.143}$$

$$p_{H_2O} = 7.329 \text{ kPa}$$

$$y_{H_2O} = \frac{p_{H_2O}}{p_{total}} ; y_{H_2O} = \frac{7.329}{105} = 0.0698 \text{ entering}$$

(a) The mol H_2O entering = $(5000)(0.0698) = 349 \text{ kg mol } H_2O / \text{hr}$

H_2O balance on condenser:

Solutions Chapter 18

(b) $W = 349 - 91 = 258 \text{ kg mol } H_2O / \text{hr}$

$$W = \frac{258 \text{ kg mol } H_2O}{18 \text{ kg } H_2O} \times \frac{18 \text{ kg } H_2O}{\text{kg mol } H_2O} = 4644 \text{ kg } H_2O / \text{hr condenses}$$

(c) dry air enters the condenser = $5000 - 349 = 4651 \text{ kg mol}$

$$\text{Stream B: } \begin{pmatrix} H_2O & 91 \text{ kg mol} \\ \text{dry air} & 4651 \text{ kg mol} \end{pmatrix} \rightarrow 4742 \text{ kg mol}$$

The air leaving the condenser in B is saturated.

$$p_{H_2O} = p_{total} y_{H_2O} = 100 \left(\frac{91}{4742} \right) = 1.919 \text{ kPa corresponding to } 17^\circ\text{C}$$

(d) In C y_{H_2O} is still $(91/4742)$; $95(91/4742) = 1.82 \text{ kPa} \rightarrow 17^\circ\text{C}$

18.22

Basis: $100 \text{ m}^3 \text{ air}$

(a) $p^*_{H_2O}$ at $21^\circ\text{C} = 0.3628 \text{ psia} = p_{H_2O}$

$$p_{H_2O} / p_t = V_{H_2O} / V_t = 0.01$$

$$p_t = 0.3628 / 0.01 = 36.28 \text{ psia}$$

(b) $S = (p)^{1.4} + (350 - T)^{1.9}$

Also p and T are related by the vapor pressure curve for water since the gas has to be saturated for condensation to take place. From Lange's Handbook,

$$\log_{10} p^* = 8.10765 - \left(\frac{1750.286}{235.0 + T} \right) \text{ for } T < 60^\circ\text{C}$$

(continued)

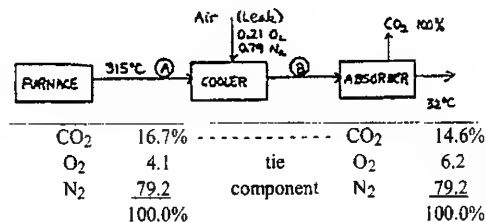
Solutions Chapter 18

For minimum cost:

$$\frac{ds}{dT} = 0 = \left[\frac{d[(p)^{1.4} + (350 - T)^{1.9}]}{dT} \right]_p + \left[\frac{d[(p)^{1.4} + (350 - T)^{1.9}]}{dp} \right]_T \frac{dp}{dT}$$

where $dp/dT = (2.3)(175.28)(p)/(T - 38)^2$. Solving the equations simultaneously, economical values are 5.8 psia, 76°C.

18.23



For dry air leaking:

Basis: 100 kg mol dry gas to absorber

CO₂ Balance:

$$\frac{100 \text{ kg mol at (B)}}{14.6 \text{ kg mol CO}_2} \left| \frac{16.7 \text{ kg mol CO}_2}{100 \text{ kg mol at (A)}} \right| = 1.144 \text{ mol gas (B)/mol gas at (A)}$$

$$1.144 - 1.00 = 0.144 \text{ mol air leaking in/mol gas at (A)}$$

You can calculate the same result using C, O, and N balances

Solutions Chapter 18

$$\frac{0.144 \text{ kg mol air leaking}}{1.00 \text{ kg mol (A)}} \left| \frac{1.00 \text{ kg mol gas at (A)}}{1.44 \text{ kg mol at (B)}} \right| = 0.126 \text{ mol dry air/mol (B)}$$

$$= 0.126 \frac{\text{m}^3 \text{ air at T and p}}{\text{m}^3 \text{ dry gas at (B) at T and p}}$$

If we assume that the gas leaving the cooler is saturated with water vapor at 32°C:

$$p_{32^\circ\text{C}, \text{H}_2\text{O}} = 4.72 \text{ kPa}$$

$$p_{\text{dry gas}} = 101.3 - 4.72 = 96.28 \text{ kPa}$$

$$\frac{n_{\text{total at B}}}{n_{\text{dry gas at B}}} = \frac{p_{\text{total}}}{p_{\text{dry gas at B}}} = \frac{101.3}{96.28} = 1.052$$

$$n_{\text{total at B}} = 100(1.052) = 105.2 \text{ kg mol}$$

$$\frac{n_{\text{leaked}}}{n_{\text{total at B}}} = \frac{V_{\text{leaked at T and p}}}{V_{\text{total at T and p}}} = \frac{0.144}{105.2} = 0.137 \frac{\text{m}^3 \text{ at T and p}}{\text{m}^3 \text{ at T and p}}$$

18.24

Basis: 1 hr 400 (0.50) = 200 lb dry sludge

$$\frac{200 \text{ lb dry sludge}}{90 \text{ lb dry sludge}} \left| \frac{10 \text{ lb H}_2\text{O}}{90 \text{ lb dry sludge}} \right| = 22.2 \text{ lb H}_2\text{O leaving}$$

Sludge Balance:

in out

$$\text{Weight of H}_2\text{O removed} = 200 - 22.2 = 177.8$$

(continued)

Solutions Chapter 18

Less centrifuge removal = 100.0

Wet water remaining (goes into air) = 77.8 lb/hr

70 °F } $p^* = 0.363 \text{ psi} = 18.6 \text{ mm Hg}$
 50%RH } $p_{H_2O} = (0.5)18.6 = 0.0124 \text{ mol H}_2\text{O}$ [BDA = bone
 760 mmHg } pair 750.7 mol BDA

dry air]

100°F } $p^* = 0.790 \text{ psia} = 40.8 \text{ mm Hg}$
 94°F dewpt } $p_{H_2O} = 40.8 = 0.0577 \text{ mol H}_2\text{O}$
 750 mmHg } pair 709 mol BDA

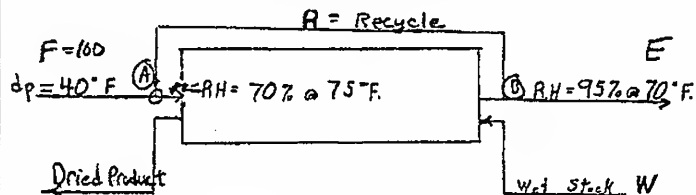
$0.0575 - 0.0124 = 0.0451 \text{ mol H}_2\text{O gained/mol BDA}$

$$\frac{1 \text{ mol BDA}}{0.0451 \text{ mol H}_2\text{O}} \left| \frac{77.8 \text{ lb H}_2\text{O}}{1 \text{ hr}} \right| \frac{1 \text{ lb mol H}_2\text{O}}{18 \text{ lb H}_2\text{O}} = 95.7 \frac{\text{lb mol BDA}}{\text{hr}}$$

Volume of moist air req'd is: $95.7 (1.024) \left(\frac{530}{492} \right) (359) = 37,920 \text{ ft}^3 \text{ at } 70^\circ\text{F}, 760 \text{ mm Hg}$

18.25

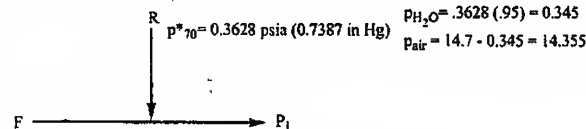
Basis: 100 lb mol dry air in fresh feed



Solutions Chapter 18

Assume $p = 14.7 \text{ psia}$

System: mixing point (A)



$p_{40}^* = 0.1217 \text{ psia (0.2478 in Hg)}$ $p_{75}^* = 0.4296 \text{ psia (0.8748 in Hg)}$

$p_{H_2O} = \boxed{0.1217}$ $p_{H_2O} = 0.4296(.70) = \boxed{0.300}$

$p_{air} = 14.7 - 0.1217 = \frac{14.58}{14.7}$ $p_{air} = 14.7 - .300 = \frac{14.4}{14.7}$

Unknowns: R, P_1 Balances: $\text{H}_2\text{O}, \text{air}$

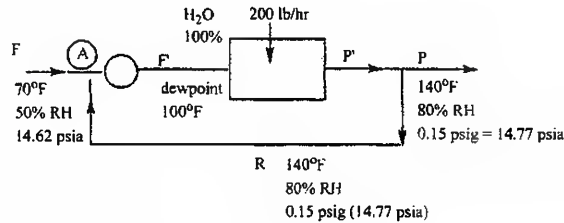
Total: $F + R = P_1$
 $\text{H}_2\text{O}: F \left(\frac{0.1217}{14.7} \right) + R \left(\frac{0.345}{14.7} \right) = P_1 \left(\frac{0.300}{14.7} \right)$ solve with $F = 100$ or another basis

$R = 396.2 \text{ lb mol}$ $P_1 = 496.2 \text{ lb mol}$

outside air = $\frac{100}{496.2} = 0.2$ recycle = $\frac{396.2}{496.2} = 0.8$

Solutions Chapter 18

18.26



Barometer = 14.62 psia

Data about compositions

	F	F'	P and R
$\dot{n}_{H_2O}$	0.3628	0.9487	2.887
$\dot{n}_{H_2O}$	$(0.5)(.3628)$ $= 0.1814$	0.9487	$(0.8)(2.887)$ $= 2.3096$
P_{total}	14.62	14.77 (assumed)	14.77
P_{air}	14.4386	13.8213	12.4604

Basis: 1 hr (better than F or P = 100)

Overall: Balances 2, unknowns 2 (F, P)

Solutions Chapter 18

$$\begin{aligned} H_2O: & F \left(\frac{0.1814}{14.62} \right) + \frac{200}{18} = P \left(\frac{2.3096}{14.77} \right) \\ Air: & F \left(\frac{14.4386}{14.62} \right) = P \left(\frac{12.4604}{14.77} \right) \end{aligned} \quad \left. \begin{array}{l} \text{Solution:} \\ F = 65.09 \\ P = 76.20 \end{array} \right\}$$

$$\text{Total: } F + \frac{200}{18} = P$$

Mixing point (A): Balances 2, unknowns 2 (R, F')

$$\begin{aligned} H_2O: & 65.09 \left(\frac{0.1814}{14.62} \right) + R \left(\frac{2.3096}{14.77} \right) = F' \left(\frac{0.9487}{14.77} \right) \\ air: & 65.09 \left(\frac{14.4386}{14.62} \right) + R \left(\frac{12.4009}{14.77} \right) = F' \left(\frac{13.8213}{14.77} \right) \end{aligned} \quad \left. \begin{array}{l} \text{Solution:} \\ R = 36.56 \\ F' = 100.7 \end{array} \right\}$$

$$\text{Total: } F + R = F'$$

$$V_R = \frac{n_R RT_R}{P_R} \quad V_P = \frac{n_P RT_P}{P_P}$$

$$T_R = T_P$$

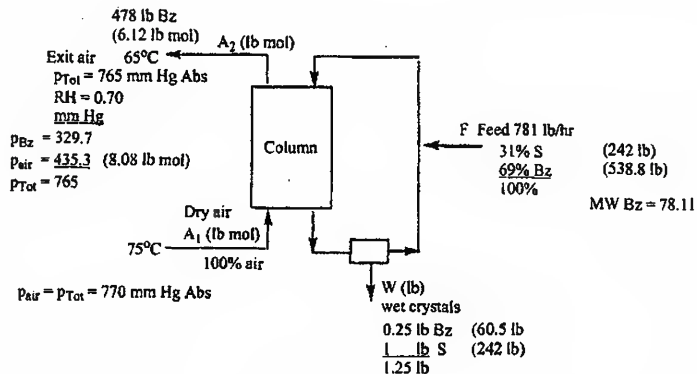
$$P_R = P_P$$

$$\frac{V_R}{V_P} = \frac{n_R}{n_P} = \frac{36.56}{76.20} = 0.48$$

Solutions Chapter 18

18.27

Steps 1-4:



Step 5: Basis: 1 hr

Step 4 cont'd: Calculate composition of A_2 p^*_{Bz} at 65°C = 471 mm Hg abs. $p_{Bz} = 0.70 (471) = 329.7$ mm Hg abs $p_{air} = 765 - 329.7 = 435.3$ mm Hg abs

Data: Vapor Pressure of Bz.

T (°C) p^* (mm Hg abs.)

60.0	396
65.0	471
70.0	553
75.0	650

Solutions Chapter 18

80.0 760

Steps 6 and 7:

Overall system:

Balances: air, Bz, S (Total balance not convenient – don't mix lb and lb mol)

Unknowns: A , A_2 , W

Steps 8 and 9: Balances in Out

S (lb): $781 (0.31) = W (1/1.25)$ $W = 302.6$ lb

air (lb mol): $A_1 (1.00) = A_2 \left(\frac{435.3}{765} \right)$

Bz (lb mol): $A_1 (0) + \frac{781(0.69)}{78.11} = \frac{302.6(0.25/1.25)}{78.11} + A_2 \frac{329.7}{765}$

Solution: $A_2 = 14.21$ lb mol $A_1 = 809$ lb mol

(a) $\frac{8.09 \text{ lb mol air}}{1 \text{ lb mol at SC}} \times \frac{359 \text{ ft}^3}{273} \times \frac{75 + 273}{770} = \frac{3654 \text{ ft}^3}{770}$ at 75°C and 770 mm Hg abs.

(b) With the present design, A will either (a) build up in the system, or (b) exit with the crystals, or (c) both.

To remove the A from the S in the product, a separator of some sort must be placed (a) before the feed, (b) after the feed but before the column, or (c) after the column but before the filter.

Solutions Chapter 18

18.28

System: the reactor

Basis: 1 mol pure benzene feed to reactor

$$(a) \text{ feed } N_2: \frac{18 \text{ mol } O_2}{21 \text{ mol } O_2} \left| \frac{79 \text{ mol } N_2}{21 \text{ mol } O_2} \right. = 67.7 \text{ mol } N_2$$

$$\text{total output mol: } \frac{67.7 \text{ mol } N_2}{0.80 \text{ mol } N_2} \left| \frac{1 \text{ mol out}}{0.80 \text{ mol } N_2} \right. = 84.6 \text{ mol (dry)}$$

$$\text{output } C_6H_4O_4: (84.6 \text{ mol}) (0.0076) = 0.643 \text{ mol}$$

From stoichiometric Equation (1): moles benzene reacted = 0.643 mol

H₂O entering with benzene: benzene is accompanied by H₂O vapor; benzene and H₂O are at their respective vapor pressures.

<u>T</u>	<u>P_{H₂O} (psia)</u>	<u>P_{Bz} (psia)</u>	<u>P_{total} (psia)</u>
180°F	15.681	7.510	23.191
$\frac{n_{H_2O}}{n_{benzene}} = \frac{P_{H_2O}}{P_{benzene}} = \frac{7.51}{15.68}$			

$$1 \text{ mol benzene in } \left| \frac{7.51 \text{ moles } H_2O}{15.68 \text{ moles benzene}} \right. = 0.48 \text{ mol } H_2 \text{ enter the reactor}$$

H₂O entering with air:

Solutions Chapter 18

$$\frac{P_{H_2O}}{P^*_{H_2O}} = 0.5 \quad P^*_{H_2O} \text{ at } 150^\circ F = 3.718 \text{ psia}$$

$$P_{H_2O} = (0.5) (3.718) = 1.86 \text{ psia}$$

$$P_{air} = 14.7 - 1.86 = 12.84 \text{ psia}$$

$$\frac{n_{H_2O}}{n_{air}} = \frac{P_{H_2O}}{P_{air}} = \frac{1.86}{12.84} \quad \text{mol } H_2O = \frac{84.6 \text{ mol air}}{12.84 \text{ mol air}} \left| \frac{1.86 \text{ mol } H_2O}{12.84 \text{ mol air}} \right. = 12.27 \text{ mol}$$

$$\text{Total mol } H_2O \text{ entering reactor} = 0.48 + 12.27 = 12.75 \text{ mol } H_2O$$

Element Balances about the reactor

In					Out				
<u>H₂O</u>	<u>C₆H₆</u>	<u>O₂</u>	<u>N₂</u>	<u>H₂O</u>	<u>N₂</u>	<u>O₂</u>	<u>CO₂</u>	<u>C₆H₆</u>	<u>C₆H₄O₄</u>

2O Balance:

$$\frac{12.75}{2} + 1(0) + 18 + 0 = \frac{x}{2} + 0 + y + z + 0 + 2(0.643)$$

2H balance:

$$12.75 + 3(1) + 0 + 0 = x + 0 + 0 + 0 + 3w + 2(0.643)$$

C balance:

$$0 + 6(1) + 0 + 0 = 0 + 0 + 0 + z + 6w + 4(0.643)$$

Total mol balance is not possible but we know from extra information given (N₂ = 80%) that the total exit mol are = 84.6. Four equations and four unknowns exist so the degrees of freedom are zero. Consequently, on dry basis: (continued)

Solutions Chapter 18

$$84.6 = 67.7 + y + z + w + 0.641$$

Solving simultaneously (the answers are sensitive to round off in the previous computations):

$$x = 13.98 \quad y = 13.62 \quad z = 2.48 \quad w = 0.16$$

Moles of benzene undergoing reaction by Reaction (2) = $1.0 - 0.16 - 0.643 =$

0.20 mol per mol Bz feed

Another approach is to use the extent of reaction: $\xi_1 = 0.0164$.

Balances around Dehydrator

$$\text{mol H}_2\text{O with C}_4\text{H}_4\text{O}_4: \frac{0.643 \times 88}{12} = 4.72 \text{ mol}$$

$$\text{mol H}_2\text{O by reaction: } 0.643 (1) = \underline{0.643 \text{ mol}}$$

$$\text{Total} \quad 5.36 \text{ mol}$$

$$(b) \quad \frac{\text{lb H}_2\text{O}}{\text{lb mol benzene}} = \frac{5.36 \text{ mol}}{1 \text{ lb mol H}_2\text{O}} \left| \frac{18 \text{ lb H}_2\text{O}}{1 \text{ lb mol H}_2\text{O}} \right| = \underline{96.5 \text{ lb H}_2\text{O}}$$

(c) Exit gases from scrubber are

Comp.	mol	mol %
N ₂	67.70	
O ₂	13.62	63.9
CO ₂	2.48	12.9
C ₆ H ₆	<u>0.16</u>	2.3
Total	83.96	0.2
H ₂ O	<u>21.90</u>	20.7
Total	105.9	100.0

Solutions Chapter 18

Calculation for H₂O vapor

Gas is saturated at 142°F

$$p_{\text{H}_2\text{O}}^* = 3.04 \text{ psia}$$

$$p_{\text{gas}} = 14.7 - 3.04 = 11.66 \text{ psia}$$

$$\left(\frac{p_{\text{H}_2\text{O}}}{p_{\text{gas}}} \right) = \frac{3.04}{11.66} = 0.261 \quad n_{\text{H}_2\text{O}} = 0.261(83.96) = 21.9$$

(d) Water Balance about Scrubber:

$$\text{mol H}_2\text{O added} = 21.90 + 4.70 - 13.70 = 12.90 \text{ mol}$$

$$\frac{\text{lb H}_2\text{O added}}{\text{lb mol benzene fed}} = \frac{12.90 \text{ mol}}{1 \text{ lb mol}} \left| \frac{18 \text{ lb H}_2\text{O}}{1 \text{ lb mol}} \right| = \underline{232 \text{ lb H}_2\text{O}}$$

Solutions Chapter 19

19.1

$$F = 2 - P + C = 2 - 2 + 2 = \boxed{2}$$

19.2

$$F = 2 - P + C$$

$$(a) \quad F = 2 - 2 + 1 = \boxed{1}$$

$$(b) \quad F = 2 - 3 + 2 = \boxed{1}$$

19.3

$$a. \quad F = 2 - P + C$$

$$C = 3$$

$$P = 2 \quad (\text{assume that } p \text{ is not unreasonably high})$$

$$F = 2 - 2 + 3 = \boxed{3}$$

- b. Possible variables are: pressure
 mol or mass fraction of
 H_2O
 $\left. \begin{array}{l} \text{acetic acid} \\ \text{ethyl alcohol} \end{array} \right\} \text{only 2 are independent}$

19.4

$$(a) \quad F = 2 - P + C = 2 - P + 2$$

$$\text{if } F = 0$$

$$P = 4 - F$$

$$\text{Max } \boxed{P = 4}$$

Solutions Chapter 19

$$(b) \quad F = 2 - P + C$$

$$3 = 2 - 2 + C \quad \boxed{C = 3}$$

19.5

$$C = 1$$

$$P = 2$$

$$F = 2 - 2 + 1 = 1$$

19.6

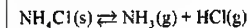
$$C = 3 \quad (\text{O}_2, \text{N}_2, \text{H}_2\text{O})$$

$$P = 2$$

$$F = 2 - 2 + 3 = \boxed{3}$$

19.7

The number of components is 3, but one independent reaction exists among them so that $C = 2$



$$P = 2$$

$$F = 2 - 2 + 2 = \boxed{2}$$

19.8

$$(1) \quad F = 2 - P + C$$

(continued)

Solutions Chapter 19

The rank of	<u>CaCO₃(s)</u>	<u>CaO(s)</u>	<u>CO₂(g)</u>
Ca	1	1	0
C	1	0	1
O	3	1	2

$\begin{bmatrix} 1 & 0 & 9 \\ 1 & 1 & 0 \\ 3 & 2 & 0 \end{bmatrix}$ is only 2 so $C = 2$

$P = 3$ hence $F = 2 - 3 + 2 = 1$

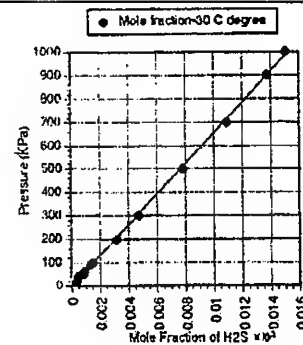
19.9

(a) F; (b) F; (c) F; (d) T; (e) T; (f) T

19.10

Henry's Law is $p = Hx$, a straight line with no intercept. A plot of the data indicates Henry's law fits the data well.

Solutions Chapter 19



19.11

Use Henry's law $p = Hx$. The MW of CHCl_3 is 119.4. The total pressure is 1 atm.

$$x = \frac{p}{H} = \frac{0.024(1)}{170} = 1.41 \times 10^{-4} \text{ mol fraction}$$

The concentration in mg/L is

$$\text{Water: } \frac{1000}{18} = 55.6 \text{ g mol/L}$$

The number of moles of CHCl_3 is

$$\frac{(55.6)(1.41 \times 10^{-4})}{1 - 1.41 \times 10^{-4}} = 7.84 \times 10^{-3} \text{ g mol/L}$$

$$\text{Concentration} = \frac{119.4 \text{ g}}{\text{g mol}} \left| \frac{7.84 \times 10^{-3} \text{ g mol}}{1 \text{ L}} \right| \left| \frac{1000 \text{ mg}}{1 \text{ g}} \right| = \boxed{940 \text{ mg/L}}$$

Solutions Chapter 19

19.12

$p = Hx$ where p is in kPa and x is mol fraction

The mole fraction of O_2 in the gas phase is y_{O_2}

$$y_{O_2} = \frac{p_{O_2}}{p_{Total}} = \frac{Hx_{O_2}}{p_{Total}}$$

The moles of O_2 and H_2O are:

$$O_2: \frac{6 \text{ mg}}{\text{L}} \left| \frac{1 \text{ g}}{1000 \text{ mg}} \right| \left| \frac{10^3 \text{ L}}{1 \text{ m}^3} \right| \left| \frac{1 \text{ g mol } O_2}{32 \text{ g } O_2} \right| = 0.1875 \text{ g mol/m}^3 \text{ in water}$$

$$H_2O: \frac{10^3 \times 10^3}{18} = 55.6 \times 10^3 \text{ g mol/m}^3$$

$$x_{O_2} = \frac{0.1875}{55.6 \times 10^3 + 0.1875} = 3.37 \times 10^{-6}$$

$$p_{Total} = 1 \text{ atm} \quad y_{O_2} = \frac{4.02 \times 10^{-6} \text{ kPa}}{\text{mol fr.}} \left| \frac{1}{101.3 \text{ kPa}} \right| \left| \frac{3.37 \times 10^{-6} \text{ mol fr.}}{\text{mol fr.}} \right| = 0.134$$

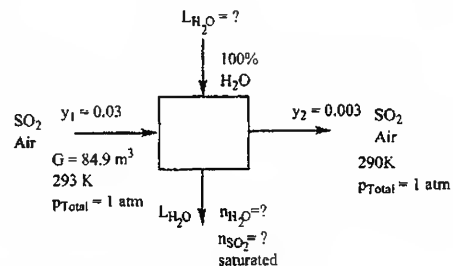
Basis: 1 L gas

$$n_{O_2} = \frac{p_{O_2}}{RT} V = \frac{(101.3 \text{ kPa})(0.134)}{101.3 \text{ kPa}} \left| \frac{1 \text{ atm}}{101.3 \text{ kPa}} \right| \left| \frac{1 \text{ L}}{0.08206 \text{ (L)(atm)}} \right| \left| \frac{(\text{g mol})(K)}{290 \text{ K}} \right| \left| \frac{18 \text{ g}}{1 \text{ g mol}} \right| \left| \frac{1000 \text{ mg}}{1 \text{ g}} \right| = \boxed{0.101 \text{ mg per L}}$$

Solutions Chapter 19

19.13

Steps 2, 3, and 4:



Step 5: Basis: 1 min (85 m³ entering gas)

Steps 6 and 7:

Unknowns: $n_{H_2O}^L, n_{SO_2}^L, \text{Air}$

Equations. Material balances: H_2O, SO_2, Air
 $y_i > Hx_i$

Steps 8 and 9:

The liquid and vapor are assumed to be in equilibrium at the exit, and the water is saturated with SO_2 so that

$$y_1 = Hx_1$$

$$0.03 = (43) x_{SO_2} \text{ so that } x_{SO_2} = 0.00070 \text{ mol fraction}$$

(continued)

Solutions Chapter 19

Material balance SO_2 (moles):

$$G(0.03 - 0.003) = L(0.00070 - 0)$$

$$\text{b. } \frac{L}{G} = \frac{38.6 \frac{\text{g mol H}_2\text{O}}{\text{g mol air}}}{1}$$

The respective flow rates are

$$G = \frac{85 \text{ m}^3}{0.024 \text{ m}^3} \left| \frac{1 \text{ g mol gas}}{1} \right| = 3540 \text{ g mol gas}$$

$$L = (3540)(38.4) = 137 \times 10^3 \text{ g mol water}$$

In terms of kg

$$\text{a. } L = (136)(18) = 2450 \text{ kg/min}$$

19.14

Steps 2, 3, and 4

$p_{\text{Total}} = 1 \text{ atm}$ and at 60°F the vapor pressures are:

$$p_{\text{Toluene}}^* = 16 \text{ mm Hg} \quad p_{\text{Benzene}}^* = 60 \text{ mm Hg}$$

Assume the mixture to be ideal so that Raoult's Law applies

Step 5: Basis: 1 mol liquid

Steps 6-9:

$$y_i = \frac{p_i}{p_{\text{Total}}} = \frac{p_i^* x_i}{p_{\text{Total}}}$$

Solutions Chapter 19

For toluene:

$$y_{\text{Tol}} = \frac{(16)(0.60)}{760} = 0.0126$$

For benzene:

$$y_{\text{Bz}} = \frac{(60)(0.40)}{760} = 0.0316$$

The balance is air.

0.0126	Toluene	
0.0316	Benzene	The vapor is flammable.
0.0442	Total	

19.15

Use Raoult's Law.

$$p_{\text{Total}} = p_r^*(1 - x_B) + p_B^* x_B$$

From Perry the vapor pressures are:

$$p_{\text{Propane}}^* = 16.8 \text{ atm}$$

$$p_{\text{Butane}}^* = 4.8 \text{ atm}$$

$$p_{\text{Total}} = (100/14.7) \text{ atm} = 6.80 \text{ atm}$$

$$6.80 = 16.8(1 - x_B) + 4.8x_B$$

$$x_{\text{Butane}} = 0.83 \text{ assuming the liquid phase is essentially all of the mixture.}$$

19.16

Mole fraction in the liquid phase is given by solving the following equations for x_{Bz} :

$$y_{\text{Bz}} = p_{\text{Bz}}^* x_{\text{Bz}} / p_{\text{Total}} \quad \text{and} \quad y_{\text{Tol}} = p_{\text{Tol}}^* x_{\text{Tol}} / p_{\text{Total}} \quad \text{to get} \quad x_{\text{Bz}} = (p_{\text{Total}} - p_{\text{Tol}}^*) / (p_{\text{Bz}}^* - p_{\text{Tol}}^*)$$

The corresponding equilibrium mole fraction in vapor phase (y) is,

(continued)

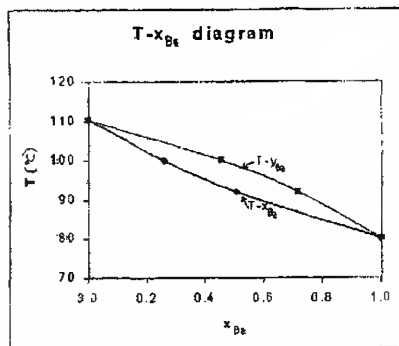
Solutions Chapter 19

$$y_i = p_i^* x_i / p_{\text{Total}}$$

Using these equations for the various temperatures given, the following data for x and y are obtained for the total pressure of 1 atm

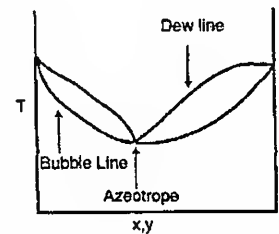
T(°C)	x_{Bz}	y_{Bz}
80	1.000	1.000
92	0.508	0.720
100	0.256	0.453
110.4	0.000	0.000

From the above-calculated data, the following T-x diagram can be drawn.



Solutions Chapter 19

19.17



19.18

Use the Antoine equation or the physical property package on the CD to get the vapor pressure of pentane (P) and heptane (H). Assume ideal liquid and vapor.

Basis: Data given in problem statement

$$\ln p_P^* (\text{mm}) = 15.8333 - \frac{2477.07}{T - 39.94} \quad p_P^* = 283.6 \text{ mm Hg (5.48 psia)}$$

$$\ln p_H^* (\text{mm}) = 15.8737 - \frac{2911.32}{T - 56.51} \quad p_H^* = 20.6 \text{ mm Hg (0.46 psia)}$$

Convert mass fractions to mole fractions:

(continued)

Solutions Chapter 19

Basis: 100 g liquid

	g	MW	$\frac{g}{mol}$	$\frac{mol}{ft.}$
P	20	72.15	0.28	0.23
H	80	86.17	0.93	0.77
	100		1.21	1.00

Equations to use, $i = P$ and H

$$\sum y_i = 1 \quad y_i = \frac{p_i x_i}{p_{Total}}$$

$$a. \quad \frac{p_P}{p_{Total}} x_P + \frac{p_H}{p_{Total}} x_H = 1 \quad p_{Total} = (283.6)(0.23) + 20.6(0.77) = \boxed{80.95 \text{ mm Hg}}$$

3.19 in Hg
10.8 kPa
1.57 psia

$$b. \quad y_i = \frac{p_i x_i}{p_{Total}} \quad y_P = \frac{16}{4.07}(0.23) = \boxed{0.90}$$

$$y_H = \frac{0.5}{4.07}(0.77) = \boxed{0.10}$$

$$\frac{0.90}{1.00}$$

19.19

The mole fractions of each component are needed to apply Raoult's law. Assuming a basis of 100 g of solution, we can construct the following:

	g	Molecular weight	Mol	Mol fraction
Water	25	18	1.39	0.37
Methanol	75	32	2.34	0.63
			3.73	1.00

Solutions Chapter 19

Raoult's law is used to compute the vapor pressure (p^*) of pure methanol based on the partial pressure required to flash:

$$p = x p^*$$

$$p^* = p/x = 62/0.63 = 98.4 \text{ mm Hg.}$$

Use the Antoine equation to get T

$$\ln(p^*) = 18.5875 - \frac{3626.55}{-34.29 + T} \quad T = \boxed{293 \text{ K}} (20^\circ\text{C})$$

19.20

Data:

	MW	p^* at 60°C
Benzene (B)	78.1	51.3 kPa
Toluene (T)	92.1	18.5 kPa

Assume ideal gas and liquid. Apply Raoult's Law. Calculate mole fractions in the liquid.

$$b. \quad x_B = \frac{1}{\frac{1}{78.1} + \frac{1}{92.1}} = \boxed{0.541}$$

$$x_T = \frac{1}{\frac{1}{92.1} + \frac{1}{78.1}} = \boxed{0.459}$$

a. The equations to use are

$$x_B p_{tot} = x_B p_B^*$$

$$y_T p_{tot} = x_T p_T^*$$

$$y_B + y_T = 1$$

$$y_B + x_T = 1$$

(continued)

Solutions Chapter 19

$$(1 - y_B)p_{\text{tot}} = x_T p_T^*$$

$$\left(1 - \frac{x_B p_B^*}{p_{\text{tot}}}\right) p_{\text{tot}} = x_T p_T^*$$

$$p_{\text{tot}} = x_B p_B^* + x_T p_T^* = (0.541)(51.3) + (0.459)(18.5) = \boxed{36.2 \text{ kPa}}$$

(b) What will be the composition of this first bubble?

$$y_B = \frac{x_B p_B^*}{p_{\text{tot}}} = \frac{(0.541)(51.3)}{36.2} = \boxed{0.766}$$

$$y_T = 1 - y_B = \boxed{0.234}$$

19.21

Data:

	p^* at -31.2°C (kPa)
Propane (P)	160.0
n-butane (B)	27.6

Assume ideal solution and vapor. Use Raoult's law

$$(a) \quad y_P p_{\text{total}} = x_P p_P^* \quad y_P + y_B = 1$$

$$y_B p_{\text{total}} = x_B p_B^* \quad y_P + y_B = 1$$

$$y_P = \frac{x_P p_P^*}{p_{\text{total}}} \quad (1 - y_P) p_{\text{total}} = (1 - x_P) p_B^*$$

More manipulations give

$$x_P = \frac{p_{\text{total}} - p_B^*}{p_P^* - p_B^*} = \frac{101.3 - 26.7}{160.0 - 26.7} = \boxed{0.56}$$

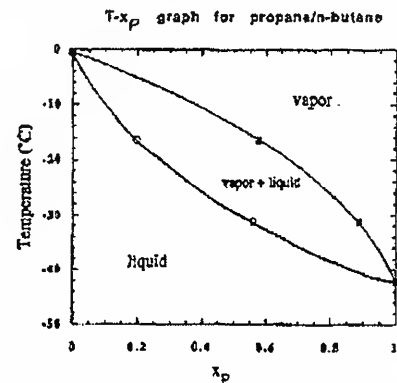
Solutions Chapter 19

$$x_B = 1 - 0.56 = 0.44$$

$$(b) \quad y_P = \frac{(0.56)(160.0)}{101.3} = \boxed{0.884} \quad y_B = 1 - 0.884 = \boxed{0.116}$$

(c) For propane

$T^\circ\text{C}$	x	y
-0.5	0.0	0.0
-16.3	0.196	0.577
-31.2	0.560	0.884
-42.1	1.0	1.0



19.22

Basis: 1.0 lb mol of mixture @ 200°C

Data:

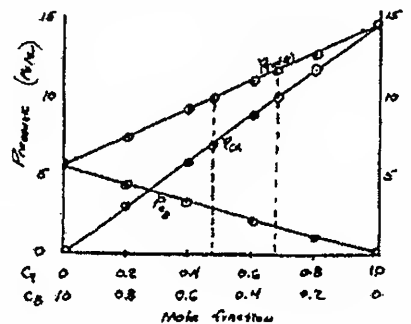
(continued)

Solutions Chapter 19

p^*_C , @ 200°F = 14.7 psia

p^*_C , @ 200°F = 5.5 psia

Mole fraction C_7	0	0.2	0.4	0.6	0.8	1.0
Partial Press C_7	0	2.94	5.88	8.82	11.75	14.7
Partial Press C_8	5.5	4.40	3.30	2.20	1.10	0
	5.5	7.34	9.18	11.02	12.75	14.7



$C_7 = 0.47$: $p_{\text{Tot}} = 11.7$ psia

For $p_{C_7} = 10.0$ psia

$p_{C_8} = 1.7$ psia

19.23 Assume ideal solution.

For the bubblepoint

$$p_{\text{Total}} = p^*_1(T)x_1 + p^*_2(T)x_2 \quad (1)$$

$p_{\text{Total}} = 200$ psia or 10,342 mm Hg

Solutions Chapter 19

x_i (mol fr.)

$$0.20 \text{ n-pentane} \quad p^*_1 = \exp \left[15.8333 - \frac{2477.07}{(-39.94 + T)} \right] \quad (2)$$

$$0.80 \text{ n-hexane} \quad p^*_2 = \exp \left[15.8366 - \frac{2697.55}{(-48.78 + T)} \right] \quad (3)$$

p^*_i is mm Hg and T is in K

Solve Equation (1) to get from Polymath $T = 447 \text{ K}$

19.24 Assume ideal solution

For the dewpoint

$$\frac{1}{p_{\text{Total}}} = \frac{y_1}{p^*_1} + \frac{y_2}{p^*_2} \quad (1)$$

$p_{\text{Total}} = 100$ psia or 5, 171 mm Hg

y_i (mol fr.)

$$0.20 \text{ n-pentane} \quad p^*_1 = \exp \left[15.8333 - \frac{2477.07}{(-39.94 + T)} \right] \quad (2)$$

$$0.80 \text{ n-hexane} \quad p^*_2 = \exp \left[15.8366 - \frac{2697.55}{(-48.78 + T)} \right] \quad (3)$$

p^*_i is mm Hg and T is in K

Solve Equation (1) to get from Polymath $T = 413 \text{ K}$

Solutions Chapter 19

19.25

Calculate the bubble point and dew point temperatures at 39.36 in. Hg = 1000 mm Hg. Use the Antoine equations to get p^* based on the assumption the solution is ideal.

$$\ln p^* = A - \frac{B}{C+T} \quad \begin{array}{l} 1 = \text{Benzene} \\ 2 = \text{Toluene} \end{array}$$

$$K_i = \frac{p_i^*}{p_i} \quad \ln(K_i) = \ln(p_i^*) - \ln(p_i) = \ln(p_i^*) - 6.9078$$

Calculate $\ln K_1$ and $\ln K_2$. Solve the bubble point equation and the dew point equation by a computer code (or Newton's method) starting with $T = 365\text{K}$ (slightly above p^* for benzene).

a. Bubble point temperature

$$\sum y_i = 1 = \sum K_i x_i$$

$$\text{If solution is ideal} \quad K_i x_i = \frac{p_i^* x_i}{p_i} \quad \text{and} \quad 0.5 \frac{p_1^*}{p_i} + 0.5 \frac{p_2^*}{p_i} - 1 = 0 \quad (1)$$

Use the Antoine equation to get p^* ,

$$\text{Benzene } p_1^* = 15.9008 - \frac{2788.51}{-52.36 + T}$$

$$\text{Toluene } p_2^* = 16.0137 - \frac{3096.52}{-53.67 + T}$$

Solution of Equation (1) using Polymath: Bubble point temperature is $\boxed{375\text{ K}}$

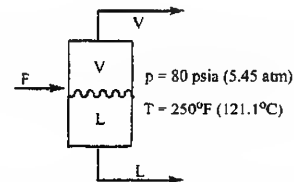
b. Dew point temperature

Solutions Chapter 19

$$\sum x_i = 1 = \sum \frac{y_i}{K_i} = \frac{0.5}{K_1} + \frac{0.5}{K_2} \quad (2)$$

Solution of Equation (2): Dewpoint temperature is $\boxed{381.5\text{ K}}$

19.26



Assume ideal liquid and vapor exist.

Vapor pressure data at 121°C from the Antoine equation (refer to problem P19.23 for the equations)

	p^* (atm)
Pentane (P)	9.07
Hexane (H)	4.03

$$p_p = p^* x_p = 9.07 x_p$$

$$p_H = p^* (1 - x_p) = 4.03(1 - x_p)$$

$$p_{\text{Total}} = 5.45 = p_p + p_H = 9.07 x_p + 4.03(1 - x_p)$$

$$\text{b. } x_p = \boxed{0.282} \quad (0.718 \text{ hexane})$$

$$y_p = \frac{p_p}{p_{\text{Total}}} = \frac{p^* x_p}{p_{\text{Total}}} = \frac{(9.07)(0.282)}{5.45} = \boxed{0.469} \quad (0.531 \text{ hexane}) \quad (\text{continued})$$

Solutions Chapter 19

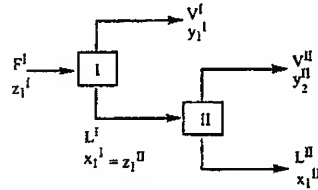
a. Basis: $F = 1 \text{ mol}$

$$F = L + V \quad L = 1 - V$$

$$F(x_F) = Lx + Vy \quad 1(0.40) = (1-V)(0.282) + V(0.469)$$

$$L = 0.37 \text{ mol} \quad V = 0.63 \text{ mol}$$

19.27



1 designates component A
2 designates component B

For each of the separation units we can write a mass balance and an equilibrium relationship, e.g., Raoult's Law.

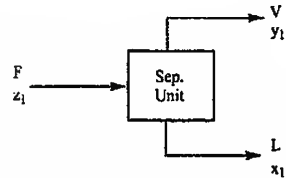
Material balance on Comp. 1

$$Fz_1 = Vy_1 + Lx_1 \quad (1)$$

Raoult's Law

$$y_1 p_{\text{Total}} = x_1 p_1^* \quad (2)$$

$$(1-y_1) p_{\text{Total}} = (1-x_1) p_2^* \quad (3)$$



Solutions Chapter 19

Solve for y_1 in (1):

$$y_1 = \left(\frac{Fz_1}{V} \right) - \left(\frac{L}{V} \right) x_1 \quad (4)$$

Introduce in (2):

$$\left[\left(\frac{Fz_1}{V} \right) - \left(\frac{L}{V} \right) x_1 \right] p_{\text{Total}} = x_1 p_1^*$$

Basis: 1 minute

Introduce the given values

$$p_1^* = 10 \text{ kPa} \quad p_2^* = 100 \text{ kPa}$$

$$F^I = 100 \text{ mol} \quad L^I = 50 \text{ mol}$$

$$V^I = 50 \text{ mol} \quad V^{II} = 25 \text{ mol}$$

$$L^{II} = 25 \text{ mol}$$

$$z_1 = 0.50$$

The solution is

$$p_1^* = 10 \text{ kPa} \quad p_2^* = 10 \text{ kPa}$$

$$p_2^* = 100 \text{ kPa} \quad p_2^* = 100 \text{ kPa}$$

Unit I	Unit II
$F^I = 100 \text{ mol/s}$	$F^{II} = 50 \text{ mol/s}$
$L^I = 50 \text{ mol/s}$	$L^{II} = 25 \text{ mol/s}$
$V^I = 50 \text{ mol/s}$	$V^{II} = 25 \text{ mol/s}$
$z_1^I = 0.5$	$z_1^{II} = 0.75975$

(continued)

Solutions Chapter 19

$x_1^I = 0.75975 = z_1^I$	$x_1^{II} = 0.93391$
$x_2^I = 0.24025 = z_2^I$	$x_2^{II} = 0.06609$
$y_1^I = 0.24025$	$y_1^{II} = 0.58559$
$y_2^I = 0.75975$	$y_2^{II} = 0.41441$
$P_{Total}^I = 31.62 \text{ kPa}$	$P_{Total}^{II} = 15.95 \text{ kPa}$

19.28

Assume pentane is the major contributor to the gas-phase composition.

$$y_i = \frac{p_i}{p_{tot}}$$

For Raoult's law,

$$p_i = p_i^* x_i \quad \text{so} \quad p_i^* = \frac{y_i p_{tot}}{x_i} = \frac{(0.018)(100)}{0.05} = 36 \text{ kPa}$$

Using the Antoine equation,

$$\ln(36) = 15.8333 - \frac{2477.07}{-39.94 + T}$$

$$T = 242 \text{ K}$$

19.29

Basis: $p_{Nap}^* @ 180^\circ \text{F} = 460 \text{ mm Hg}$

$$p_{H_2O}^* @ 180^\circ \text{F} = 388 \text{ mm Hg}$$

$$P_{Max} = P_{H_2O} + P_{Naptha} = 460 + 388 = 848 \text{ mm Hg} \quad (a)$$

Solutions Chapter 19

$$p_{Naptha}^* @ 160^\circ \text{F} = 318 \text{ mm Hg}$$

$$p_{H_2O}^* @ 160^\circ \text{F} = 245 \text{ mm Hg}$$

Basis: 6000 lb feed $(5000)(0.928) = 4640 \text{ lb pure Naptha}$

$$\frac{\text{lb mol } H_2O}{\text{lb mol Nap}} = \frac{245}{318} = 0.77$$

$$\frac{W_1}{W_2} = \frac{n_1 M_1}{n_2 M_2}; W_1 = 4640 \left(\frac{18}{107} \right) (0.77) = 600 \text{ lb } H_2O \text{ Distilled}$$

$$1000 - 600 = 400 \text{ lb } H_2O \text{ left} \quad (b)$$

19.30

Assume that the pressure at the bottom of the lake = p_{CO_2}

$$p = pgh \text{ varies with height}$$

$$\text{Avg. depth} = 225 \text{ m}$$

$$p_{CO_2} = \frac{1000 \text{ kg}}{\text{m}^3} \left| \frac{9.8 \text{ m}}{\text{s}^2} \right| \frac{225 \text{ m}}{\text{s}^2} = 2.21 \times 10^3 \text{ kPa} + 1.01 \times 10^2 \text{ kPa} = 23 \text{ atm}$$

$$p_{CO_2} = H x_{CO_2} \Rightarrow x_{CO_2} = \frac{23 \text{ atm}}{1.7 \times 10^3 \text{ atm/mol fr}} = 0.0134$$

If the entire 200,000 tons were saturated at p_{CO_2} but not supersaturated

$$\frac{200,000 \text{ ton } H_2O}{1} \left| \frac{1000 \text{ kg}}{\text{ton}} \right| \frac{1 \text{ kg mol}}{18 \text{ kg}} = 1.11 \times 10^7 \text{ kg mol} \quad (\text{continued})$$

Solutions Chapter 19

$$0.0134 = \frac{n_{\text{CO}_2}}{1.11 \times 10^7 + n_{\text{CO}_2}} \quad n_{\text{CO}_2} \text{ is mol of CO}_2$$

$$n_{\text{CO}_2} = 1.51 \times 10^5 \text{ kg mol}$$

$$\frac{nRT}{p} = V_{\text{CO}_2} = \frac{(1.5 \times 10^5)(8.314)(273)}{101.3 \text{ kPa}} = \boxed{3.39 \times 10^6 \text{ m}^3}$$

Above would be the worst case. The CO_2 would be less; p_{CO_2} average might be a better choice to use in which case V_{CO_2} would be, say $\frac{1}{2}$ the calculated amount.

19.31

For multiple components, the vapor pressure varies with composition as well as with temperature, and to be precise the composition should be stated.

19.32

a. Apply Henry's law to solve the problem.

$$p = Hx \quad \text{or} \quad x = \frac{p}{H}$$

From the internet, $H = 43,600$ where x is the mole fraction in the liquid and p is in bars.

Enriched gas

$$x_{\text{O}_2} = \frac{\frac{(110)(0.397) \text{ kPa}}{100 \text{ kPa}} \left| \frac{1 \text{ bar}}{100 \text{ kPa}} \right.}{43,600 \text{ bar}} = 1.00 \times 10^{-5} \text{ mol fr.}$$

Solutions Chapter 19

b. To compare enriched gas with nonenriched gas

$$\frac{x_{\text{enriched}}}{x_{\text{nonenriched}}} = \frac{\left(\frac{p}{H}\right)_{\text{enriched}}}{\left(\frac{p}{H}\right)_{\text{nonenriched}}} = \frac{(110)(0.397)}{(110)(0.21)} = 1.89$$

$$\text{percent excess is: } \frac{1.89 - 1}{1}(100) = \boxed{89\%}$$

19.33

Apply K values to solve the problem. Get the mole fraction of the compound in the liquid phase.

Basis: 100 g water (5.555 g mol)

	<u>g</u>	<u>MW</u>	<u>g mol</u>	<u>g mol</u>	liquid <u>x (mol fr.)</u>	<u>K</u>	vapor <u>y (mol fr.)</u>
				<u>H₂O</u>			
Glycerol	5.5	92.08	0.0597	5.555	0.0106	1.2×10^{-7}	1.27×10^{-9}
MEK	1.1	72.10	0.0153	5.555	0.00275	3.065	0.00843
Phenol	2.1	94.11	0.0223	5.555	0.00400	0.00485	1.94×10^{-5}

The mole fractions in the gas phase are in the far right hand column. Glycerol and phenol have the lowest concentrations. If volatilization is proportional to the vapor phase concentration, only MEK might be a problem.

Solutions Chapter 20

20.1

The Langmuir equation is

$$y = \frac{(1 + A)p}{1 + Bp} = \frac{p + Ap}{1 + Bp}$$

The Freundlich isotherm for a gas

$$y = kp^n$$

y = uptake in mg mol/g adsorbent and p is the partial pressure of the SO_2 . A , B , k , and n are coefficients in the respective equations.

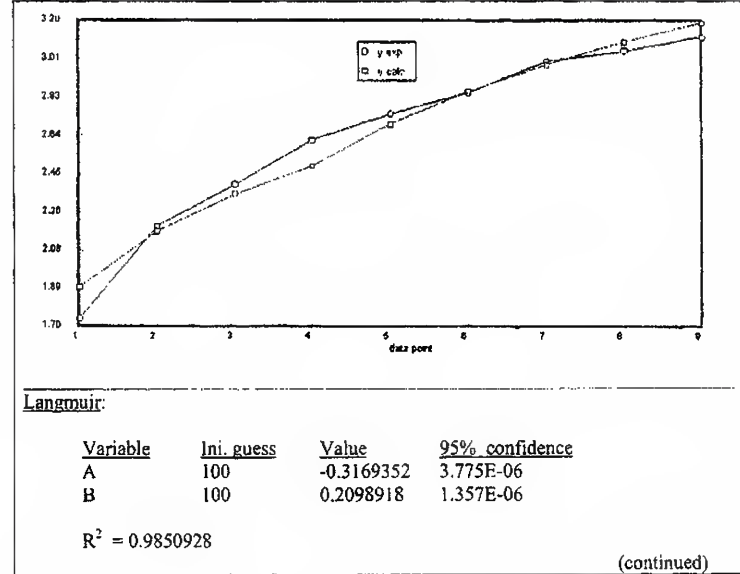
Fit the data using Polymath. The results are:

Freundlich:

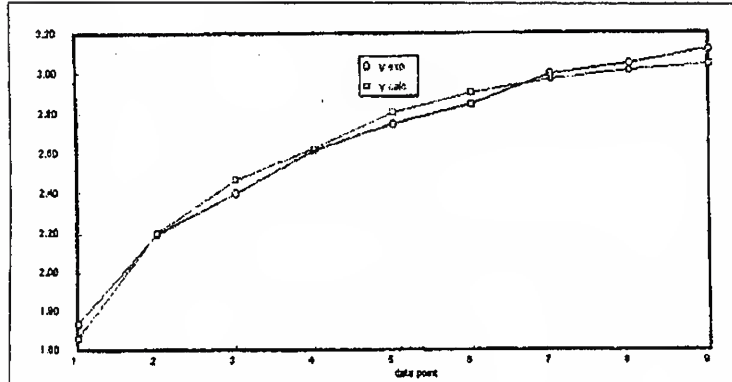
Variable	Ini. guess	Value	95% confidence
k	100	1.3807516	0.1692861
n	3	0.197042	0.0345842

$R^2 = 0.9676593$ Fit is reasonably good.

Solutions Chapter 20



Solutions Chapter 20



20.2

Refer to Problem 20.1 for the equations. Transformation of the uptake to mg mol/g gel is

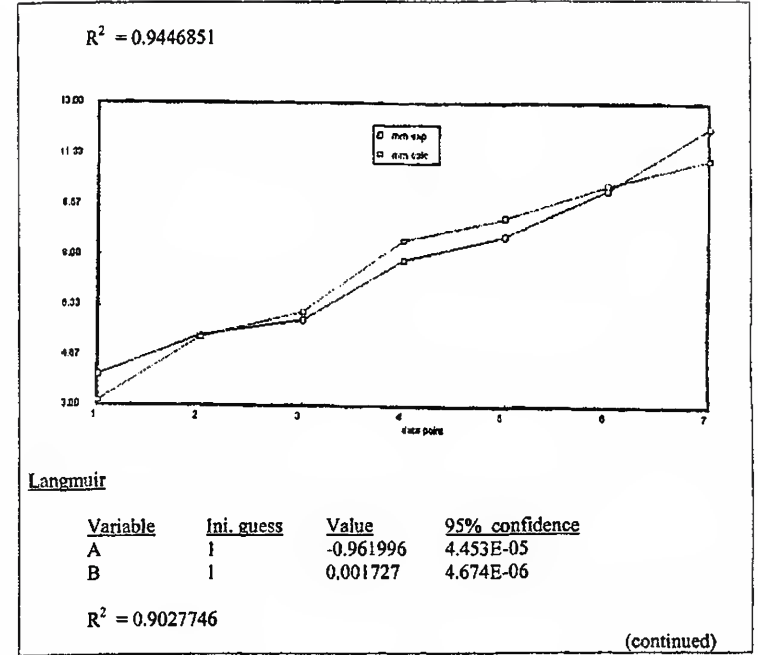
mg mol	mg mol/g gel
2.456	4.053
3.247	5.358
3.571	5.893
4.762	7.858
5.248	8.660
6.168	10.178
7.413	12.233

Results from Polymath:

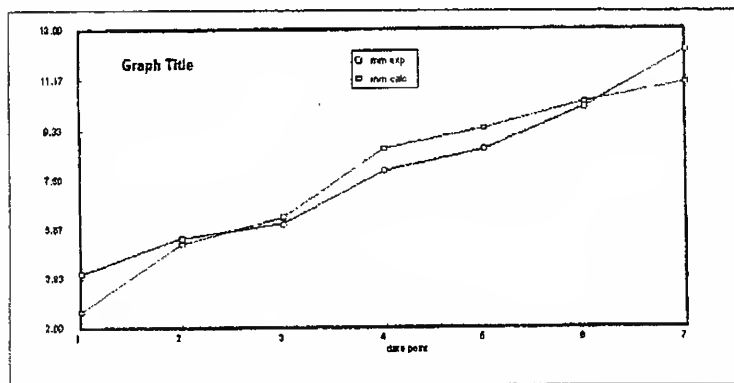
Freundlich

Variable	Ini. guess	Value	95% confidence
k	1	2.2075306	0.2616611
n	1	0.6259709	0.2086725

Solutions Chapter 20



Solutions Chapter 20



20.3

Refer to Problem 20.1 for the equations. Transformation of the uptake to mg mol/g is

0.0026
0.0142
0.0731
0.1613
1.0859
1.5301
1.7114
1.8649
1.9657
2.0396

Results from Polymath are:

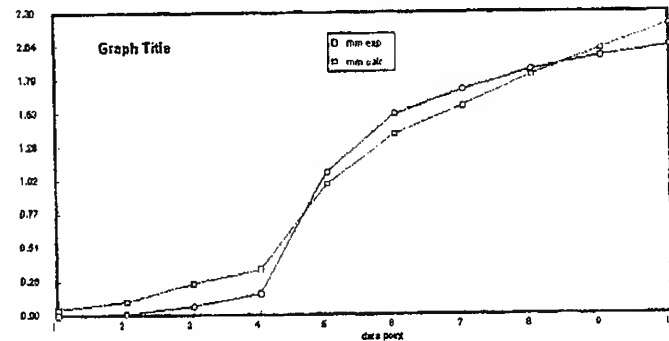
Freundlich

(continued)

Solutions Chapter 20

Variable	Ini. guess	Value	95% confidence
k	1	0.1074754	0.0470479
n	1	0.4719338	0.0733271

$$R^2 = 0.9780993$$



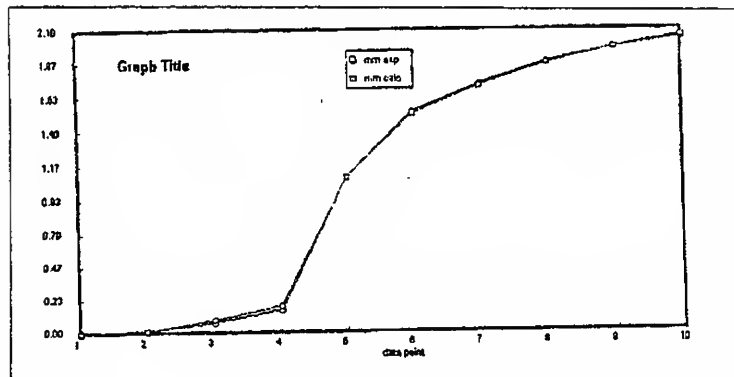
Langmuir

Variable	Ini. guess	Value	95% confidence
A	1	-0.9831	3.794E-06
B	1	0.0065856	2.08E-06

$$R^2 = 0.9998068$$

(continued)

Solutions Chapter 20



20.4

Let $c_i = 0$. Then $c_s = 1.06 c_i^{0.405}$

20.5

Basis: 1 L solution

The material balance in mg is $12 - 0.001 \approx 12$ mg/L removed from the solution. The equilibrium relation gives

$$y = 100 (0.001)^{0.30} = 12.6 \text{ mg adsorbate/g adsorbent taken up}$$

$$\frac{12 \text{ mg adsorbate}}{1 \text{ L solution}} \bigg| \frac{1 \text{ g charcoal}}{12.6 \text{ mg adsorbate}} = 0.95 \text{ g charcoal/L solution}$$

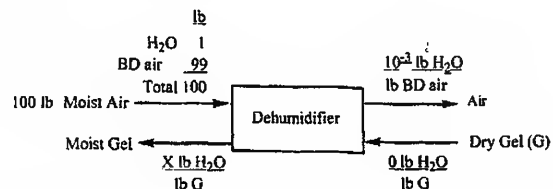
Solutions Chapter 20

20.6

Step 5: Steady State open process.

Basis: 1 minute (100 lb moist air)

Steps 2, 3, and 4:



Assume $p = 760$ mm Hg

Exit air is: 99 lb dry air and 99×10^{-3} lb H_2O

Calculate moles of water in the entering air to use in calculating the partial pressure of the water in the air.

	MW	lb mol
1 lb H_2O	18	0.0556
99 lb air	29	3.4138
100		3.469

Steps 6 and 7:

Unknowns: Dry gel (G) and X

Equations: H_2O , dry air, gel balances plus equilibrium relation

(continued)

Solutions Chapter 20

Steps 8 and 9:

Material balance on H₂O (in lb) on the humidifier:

$$\frac{\text{Out}}{(10^{-3})(99) + XG} - \frac{\text{in}}{1} = \frac{\text{Accum.}}{= 0}$$

Equilibrium relation:

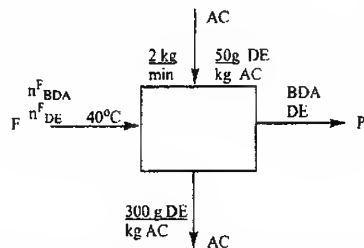
$$X \frac{\text{lb H}_2\text{O}}{\text{lb G}} = 0.0375 \left[760 \left(\frac{0.0556}{3.469} \right) \right]^{0.65} = 0.190$$

$$1 - 0.099 = 0.190 G \quad G = \boxed{4.72 \text{ lb/min}}$$

20.7

Step 5: Basis: 1 minute (2 kg activated carbon)

Steps 2, 3, and 4:



BDA is bone dry air and AC is activated carbon. The dew point of the feed is 12°C, and the barometer is 770 mm Hg. MW of DE = 98.97 and MW of BDA is 29.

Solutions Chapter 20

The entering concentration of DE in F is determined from the dewpoint

At 12°C, $p_{DE}^* = 127.95 \text{ mm Hg}$

$$y_{DE}^F = \frac{n_{DE}^F}{n_{BDA}^F} = \frac{p_{DE}^*}{p_{BDA}} = \frac{127.95}{770 - 127.95} = 0.199 \frac{\text{g mol DE}}{\text{g mol BDA}}$$

$$\frac{0.199 \text{ g mol DE}}{1 \text{ g mol BDA}} \left| \frac{98.97 \text{ g DE}}{1 \text{ g mol DE}} \right| \frac{1 \text{ g mol BDA}}{29 \text{ g BDA}} = \frac{0.679 \text{ g DE}}{\text{g BDA}} \quad (19.7 \text{ g DE/g mol BDA})$$

Steps 6 and 7:

Unknowns: DE in P and BDA in P

Material balances: DE and BDA

Steps 8 and 9:

DE balance (g of DE):

$$\frac{19.7 \text{ g DE}}{1 \text{ g mol BDA}} \left| \frac{n_{BDA}^F \text{ g mol BDA}}{1 \text{ g mol BDA}} \right| + \frac{50 \text{ g DE}}{1 \text{ kg AC}} \left| \frac{2 \text{ kg AC}}{1 \text{ kg AC}} \right|$$

$$= \frac{n_{DE}^F \text{ g DE}}{\text{g mol BDA}} \left| \frac{n_{BDA}^F \text{ g mol BDA}}{1 \text{ g mol BDA}} \right| + \frac{300 \text{ g DE}}{1 \text{ kg AC}} \left| \frac{2 \text{ kg AC}}{1 \text{ kg AC}} \right|$$

The amount of DE in the exit AC is

$$\frac{300 \text{ g DE}}{\text{kg AC}} \left| \frac{1 \text{ kg AC}}{1000 \text{ g AC}} \right| = 0.300 \text{ g DE/g AC}$$

(continued)

Solutions Chapter 20

$$0.300 = 0.089 p^{0.51}$$

$$p_{DE} = 10.83 \text{ mm Hg}$$

The amount of DE in the exit air is

$$\frac{10.83}{770 - 10.83} = 0.0143 \frac{\text{g mol DE}}{\text{g mol BDA}}$$

$$\text{or } \frac{0.0143 \text{ g mol DE}}{1 \text{ g mol BDA}} \left| \frac{98.97 \text{ g DE}}{1 \text{ g mol DE}} \right| = 1.412 \frac{\text{g DE}}{\text{g mol BDA}} = n'_{DE}$$

The mol fraction of the DE in the air is

$$\frac{0.0143}{1 + 0.0143} = 0.0141$$

The g mol of an entering (and exit) BDA are (in 1 minute)

$$19.7n + 100 = 1.412n + 600$$

$$n = \boxed{32.8 \text{ g mol BDA/min}}$$

20.8

Basis: 1 L saturated solution of nitrobenzene at 20°C

$$K_{oc} = 10^{2.27} = 186$$

$$186 = \frac{\begin{array}{c} \times \text{ mass adsorbed } (\mu\text{g}) \\ 0.11(1)(1000) \text{ g C in soil} \end{array}}{\begin{array}{c} \frac{0.19 \text{ g nitrobenzene}}{100 \text{ g water}} \left| \frac{1 \text{ g water}}{1 \text{ mL water}} \right| \frac{10^6 \mu\text{g}}{1 \text{ g}} \end{array}}$$

$$\times = \boxed{39 \text{ g nitrobenzene}}$$

Solutions Chapter 21

21.1

Basis: 1 lb_m

$$a. \frac{45.0 \text{ Btu}}{\text{lb}_m} \left| \frac{252 \text{ cal}}{1 \text{ Btu}} \right| \left| \frac{1 \text{ lb}_m}{0.454 \text{ kg}} \right| = 2.5 \times 10^4 \text{ cal/kg}$$

$$b. \frac{45.0 \text{ Btu}}{\text{lb}_m} \left| \frac{1.055 \times 10^3 \text{ J}}{1 \text{ Btu}} \right| \left| \frac{1 \text{ lb}_m}{0.454 \text{ kg}} \right| = 1.048 \times 10^5 \text{ J/kg}$$

$$c. \frac{45.0 \text{ Btu}}{\text{lb}_m} \left| \frac{2.930 \times 10^{-4} (\text{kW})(\text{hr})}{1 \text{ Btu}} \right| \left| \frac{1 \text{ lb}_m}{0.454 \text{ kg}} \right| = 2.91 \times 10^{-2} \frac{(\text{kW})(\text{hr})}{\text{kg}}$$

$$d. \frac{45.0 \text{ Btu}}{\text{lb}_m} \left| \frac{7.7816 \times 10^2 (\text{ft})(\text{lb}_f)}{1 \text{ Btu}} \right| = 3.5 \times 10^4 (\text{ft})(\text{lb}_f)/\text{lb}_m$$

21.2

$$a. \frac{4.184 \text{ J}}{(\text{g})(^\circ\text{C})} \left| \frac{9.484 \times 10^{-4} \text{ Btu}}{\text{J}} \right| \left| \frac{1 \text{ g}}{2.2 \times 10^{-3} \text{ lb}_m} \right| \left| \frac{1^\circ\text{C}}{1.8^\circ\text{F}} \right| = \frac{1.00}{(\text{lb}_m)(^\circ\text{F})}$$

$$b. \frac{-41.6 \text{ J}}{\text{kg}} \left| \frac{9.484 \times 10^{-4} \text{ Btu}}{\text{J}} \right| \left| \frac{\text{kg}}{1000 \text{ g}} \right| \left| \frac{1 \text{ g}}{2.20 \times 10^{-3} \text{ lb}_m} \right| = -0.0179 \frac{\text{Btu}}{\text{lb}_m}$$

$$c. \frac{0.59 (\text{kg})(\text{m})}{(\text{s}^3)(\text{K})} \left| \frac{1 \text{ N}}{(\text{kg})(\text{m})(\text{s}^{-2})} \right| \left| \frac{(\text{J})(\text{m}^{-1})}{1 \text{ N}} \right| \left| \frac{9.484 \times 10^{-4} \text{ Btu}}{\text{J}} \right| \left| \frac{1 \text{ m}}{3.2808 \text{ ft}} \right| \left| \frac{3600 \text{ s}}{\text{hr}} \right| \left| \frac{1 \text{ K}}{1.8^\circ\text{F}} \right|$$

$$= 0.341 \frac{\text{Btu}}{(\text{ft})(\text{hr})(^\circ\text{F})}$$

Solutions Chapter 21

21.3

$$a. \frac{6000 \text{ Btu}}{(\text{hr})(\text{ft}^2)} \left| \frac{252 \text{ cal}}{1 \text{ Btu}} \right| \left| \frac{\text{hr}}{3600 \text{ s}} \right| \left| \frac{\text{ft}^2}{30.48^2 \text{ cm}^2} \right| = 0.4521 \frac{\text{cal}}{(\text{s})(\text{cm}^2)}$$

$$b. \frac{2.3 \text{ Btu}}{(\text{lb})(^\circ\text{F})} \left| \frac{252 \text{ cal}}{1 \text{ Btu}} \right| \left| \frac{\text{lb}}{453.6 \text{ g}} \right| \left| \frac{(\Delta) 1.8^\circ\text{F}}{(\Delta) ^\circ\text{C}} \right| = 2.3 \frac{\text{cal}}{(\text{g})(^\circ\text{C})}$$

$$c. \frac{200 \text{ Btu}}{(\text{hr})(\text{ft})(^\circ\text{F})} \left| \frac{1,055 \text{ J}}{1 \text{ Btu}} \right| \left| \frac{\text{hr}}{3600} \right| \left| \frac{\text{ft}}{30.45 \text{ cm}} \right| \left| \frac{(\Delta) 1.8^\circ\text{F}}{(\Delta) ^\circ\text{C}} \right| = 3.46 \frac{\text{J}}{(\text{s})(\text{cm})(^\circ\text{C})}$$

$$d. \frac{10.73 (\text{lb}_p)(\text{ft}^3)}{(\text{in.}^2)(\text{lb mol})(^\circ\text{R})} \left| \frac{144 \text{ in.}^2}{\text{ft}^2} \right| \left| \frac{\text{Btu}}{778 (\text{ft})(\text{lb}_p)} \right| \left| \frac{\text{lb mol}}{453.6 \text{ g mol}} \right| \left| \frac{1.055 \times 10^3 \text{ J}}{1 \text{ Btu}} \right| \left| \frac{(\Delta) 1.8^\circ\text{R}}{(\Delta) ^\circ\text{K}} \right|$$

$$= 8.31 \frac{\text{J}}{(\text{g mol})(^\circ\text{K})}$$

21.4

To convert to J/(min)(cm²)(°C), we set up the dimensional equation as follows

$$h = \frac{0.026 \text{ G}^\circ\text{Btu}}{\text{D}^\circ\text{A}(\text{hr})(\text{ft}^2)(^\circ\text{F})} \left| \frac{1055 \text{ J}}{1 \text{ Btu}} \right| \left| \frac{1 \text{ hr}}{60 \text{ min}} \right| \left| \left(\frac{1 \text{ ft}}{12 \text{ in.}} \right)^2 \right| \left| \left(\frac{1 \text{ in.}}{2.54 \text{ cm}} \right)^2 \right| \left| \frac{1.8^\circ\text{F}}{1^\circ\text{C}} \right|$$

$$= 8.86 \times 10^{-4} \frac{\text{G}^\circ\text{J}}{\text{D}^\circ\text{A}(\text{min})(\text{cm}^2)(^\circ\text{C})}$$

Solutions Chapter 21

21.5

$$a. \frac{1 \text{ lb fat}}{2.2 \text{ lb}} \frac{1 \text{ kg}}{\text{kg}} \frac{7,700 \text{ k cal}}{500 \text{ k cal}} \frac{\text{day}}{\text{day}} = 7 \text{ days}$$

$$b. \frac{1 \text{ lb fat}}{2.2 \text{ lb}} \frac{1 \text{ kg}}{\text{kg}} \frac{7,700 \text{ k cal}}{1 \text{ k cal}} \frac{4,184 \text{ J}}{400 \text{ k J}} \frac{\text{km}}{1 \text{ km}} \frac{0.6214 \text{ mi}}{1 \text{ km}} = 22.75 \text{ mi}$$

c. Total energy consumed is the same. The higher power consumption is compensated for in the shorter travel time.

21.6

Basis: 10^{11} watts

$$\frac{10^8 \text{ W}}{10^3 (\text{W})(\text{hr})} \frac{8.6057 \times 10^4 \text{ cal}}{60 \text{ min}} \frac{1 \text{ hr}}{0.10} \frac{1}{32.0 \text{ cal}} \frac{(\text{min})(\text{cm}^2)}{(100 \text{ cm})^2} = 4.5 \times 10^4 \text{ m}^2 \text{ large}$$

21.7

$$a. \frac{975 \text{ W}}{\text{m}^2} \frac{1 \text{ A}}{\text{m}^2} \frac{320 \text{ days}}{1 \text{ day}} \frac{24 \text{ hr}}{24} \frac{5}{1} \frac{0.21}{1} \frac{3.6 \times 10^6 \text{ J}}{1 (\text{kW})(\text{hr})}$$

$$= 3 \times 10^{20} \text{ J}$$

$$A = 2.5 \times 10^{11} \text{ m}^2 \quad (2.5 \times 10^9 \text{ km}^2)$$

The capital cost is probably too great and the maintenance too high relative to other power sources. Also, the location would have to be in the far western united so power

Solutions Chapter 21

would have to be transmitted over long distances.

$$b. 3 \times 10^{20} \text{ J} = \frac{10,000 \text{ Btu}}{\text{lb}} \frac{2,000 \text{ lb}}{\text{ton}} \frac{T \text{ tons}}{1 \text{ Btu}} \frac{1055 \text{ J}}{1 \text{ Btu}} \frac{0.70}{1}$$

$$T = 2.0 \times 10^{10} \text{ tons}$$

$$\frac{2.0 \times 10^{10}}{1.7 \times 10^{12}} = 0.012$$

21.8

Yes. Watts are power, and if the energy is transferred for a very short period to time, the power can be quite large. For example, 1J (a very small amount of energy) transferred in 10^{-6} s is 1 MW!

21.9

First substitute for T_{re}

$$T_{\text{re}} = T_{\text{rc}}(1.8) + 32$$

Next change units

$$k = \frac{a + b[T_{\text{rc}}(1.8) + 32]}{(\text{hr})(\text{in})(^\circ\text{F})} \frac{\text{Btu}}{1 \text{ Btu}} \frac{1055 \text{ J}}{12 \text{ in}} \frac{1 \text{ ft}}{2.54 \text{ cm}} \frac{1 \text{ hr}}{60 \text{ min}} \frac{1.80^\circ\text{F}}{10 \text{ K}}$$

$$= 1.05[a + b(T_{\text{rc}}(1.8) + 32)] \frac{\text{J}}{(\text{min})(\text{cm})(\text{K})} \quad \text{or } k = 1.05 a + 1.8 b T_{\text{rc}} + 33.2$$

21.10

$$\frac{900,000 \text{ J}}{9 \times 10^{-3} \text{ s}} \frac{(s)(10^{-3}) \text{ kW}}{1 \text{ J}} = 10^8 \text{ kW or } 100 \text{ MW}$$

(continued)

Solutions Chapter 21

The answer is **yes**.

21.11

The trend is to advertise in a way that makes people select a product. And sometimes that just creates confusion.

What the manufacturer is doing is basing the advertisement on the *weight* of the hot dog. A hot dog weighs about 43 grams and has 8 grams of fat in it. They divided 8 by 43 and get 19 percent fat. They can round it off to 20 and say it's 80 percent fat free.

But you are concerned with the percentage of fat in the *calories*. You want 30 percent or less to come from fat.

Your figures are right.

21.12

(a) Some examples are:

How far would you have to run to lose 1 kg of fat?

$$\frac{32,000 \text{ kJ}}{400 \text{ kJ}} \times \frac{1 \text{ km}}{1} = 80 \text{ km}$$

about the distance of 2 marathons!

(b) How many days would you have to reduce your diet from 2400 calories to 1400 calories to lose one kg of fat?

$$\frac{7700 \text{ k cal}}{1 \text{ kg fat}} \times \frac{1 \text{ day}}{1000 \text{ k cal}} = 8 \text{ days}$$

Solutions Chapter 21

21.13

A main meal is equivalent to about 4000 kJ. A ¼ hour is 900 seconds, so that (700 J/s) (900 s) / 1000 = 630 kJ, an insufficient amount of time.

21.14

(a) T; (b) T; (c) F; (d) F; (e) T

21.15

(a) T; (b) T; (c) T; (d) T; (e) T; (f) F; (g) F

21.16

partial pressure	intensive
volume	extensive
specific gravity	intensive
potential energy	extensive
relative saturation	intensive
specific volume	intensive
surface tension	intensive
refractive index	intensive

21.17

- Intensive
- Intensive
- Intensive
- Extensive

Solutions Chapter 21

21.18

A closed system because no mass exchange occurs with the surroundings.

21.19

Basis: 40.0 Newtons $\times$ 6.00 m = 240(N)(m)

$$(a) \frac{240(\text{N})(\text{m})}{1(\text{N})(\text{m})} \left| \frac{1 \text{ J}}{1(\text{N})(\text{m})} \right| = \boxed{240 \text{ J}}$$

$$(b) \frac{240(\text{N})(\text{m})}{1(\text{N})(\text{m})} \left| \frac{0.738(\text{ft})(\text{lb}_f)}{1(\text{N})(\text{m})} \right| = \boxed{177.0(\text{ft})(\text{lb}_f)}$$

$$(c) \frac{240(\text{N})(\text{m})}{1(\text{N})(\text{m})} \left| \frac{1 \text{ J}}{1(\text{N})(\text{m})} \right| \left| \frac{0.239 \text{ cal}}{1 \text{ J}} \right| = \boxed{57.4 \text{ cal}}$$

$$(d) \frac{240(\text{N})(\text{m})}{1(\text{N})(\text{m})} \left| \frac{1 \text{ J}}{1(\text{N})(\text{m})} \right| \left| \frac{9.478 \times 10^{-4} \text{ Btu}}{1 \text{ J}} \right| = \boxed{0.226 \text{ Btu}}$$

21.20

The work done by the cylinder-piston system is $W = -p(V_2 - V_1)$

$$= - \frac{350 \text{ kPa}}{1 \text{ kPa}} \left| \frac{0.15 - 0.02 \text{ m}^3}{(1 \text{ kPa})(1 \text{ m}^3)} \right| \left| \frac{1 \text{ kJ}}{1 \text{ kPa}(1 \text{ m}^3)} \right| = \boxed{-45.5 \text{ kJ}}$$

Solutions Chapter 21

21.21

No work is done because the boundary of the system remains fixed.

21.22

Basis: 10 lb water (5 lb vaporized)

The work done by the piston is caused by the water vapor expanding at constant temperature and pressure. Ignore the volume of the liquid water at the initial conditions, and assume the initial amount of vapor is also negligible. From state to state 2

$\Delta \hat{V}_{\text{vapor}} = 4.897 \text{ ft}^3/\text{lb}$ from the steam tables. For the 5 lb

$$V_2 = (5 \text{ lb})(4.897 \text{ ft}^3/\text{lb}) = 24.49 \text{ ft}^3$$

$$W = - \frac{89.65 \text{ lb}_f}{\text{in}^2} \left| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right| \left| \frac{(24.49 \text{ ft}^3)}{1 \text{ ft}^3} \right| = \boxed{-3.16 \times 10^5 (\text{lb}_f)(\text{ft})}$$

21.23

Basis: 1.2 ft³ gas at 7.3 atmp of 1 atm = 15,450 lb_f/ft²

$$pV^{1.3} = \text{const.}$$

$$V_1^{1.3} = (1.2)^{1.3} = 1.27$$

$$p_1 V_1^{1.3} = (15450)(1.27) = 19,620$$

$$W = - \int p dV = - \int \frac{19,620}{V^{1.3}} dV = -19,620 \int \frac{dV}{V^{1.3}} = - \left[\frac{19,620}{-0.3 V^{0.3}} \right]_{V_1}^{V_2}$$

(continued)

Solutions Chapter 21

$$V_2^{1.3} = \frac{(V_1^{1.3})(p_1)}{p_2} = \frac{(1.27)(7.3)}{(1.0)} = 9.27$$

$$V_2 = 5.54 \text{ ft}^3$$

$$V_1^{0.3} = (1.2)^{0.3} = 1.06$$

$$V_2^{0.3} = (5.54)^{0.3} = 1.67$$

$$W = \frac{19,620 \left[\frac{1}{1.67} - \frac{1}{1.06} \right]}{0.3} = -\frac{(19,620)(0.344)}{0.3} = \boxed{-22,500(\text{ft})(\text{lb}_f)}$$

21.24

(a) T; (b) F; (c) T; (d) F; (e) F; (f) F; (g) T

21.25

The comment is not a correct use of the term heat, which is a transfer of energy.

21.26

Conservation is confused with balancing. Heat is energy transferred from one system to another, and from the viewpoint of either system (for which an energy balance is made), heat is not conserved. Thus (a) is wrong, heat is part of a balance; (b) same as (a); (c) heat is not conserved – it is transferred and is part of the energy balance; (d) the answer should be no with the explanation offered.

Solutions Chapter 21

21.27

- (a) Wrong. Heat is energy, not material.
- (b) Wrong. Heat is energy by definition.
- (c) Wrong. Heat is energy; cold is related to temperature.
- (d) Wrong. See (c).
- (e) Wrong. Heat is a transfer of energy.
- (f) Heat can be measured, but indirectly via temperature, mass, etc.
- (g) Wrong. See (a).
- (h) Ok except for “or can be stored” which is wrong.
- (i) Burning produces a change in the state of the reactants and products, but the change is not heat. Heat transfer can result from the change in state.
- (j) Heat cannot be stored and hence destroyed. Heat transfer can be terminated.

21.28

A better use of words than “absorbing heat” would be “to transfer heat”. Heat is really not “concentrated”. The internal energy of the medium increases.

21.29

(a) F; (b) F; (c) T; (d) F; (e) T; (f) T but debatable; (g) F; (h) F

Solutions Chapter 21

21.30

Heat transfer rate is $\dot{Q} = h A \Delta T = h(\pi DL)\Delta T$

$$\dot{Q} = \frac{5 \text{ J}}{(\text{s})(\text{m}^2)(^\circ\text{C})} \left| \frac{5 \text{ cm}}{100 \text{ cm}} \right| \left| \frac{1 \text{ m}}{100 \text{ cm}} \right| \left| \frac{100\pi \text{ m}}{100 \text{ cm}} \right| (120 - 20)^\circ\text{C} = \boxed{7854 \text{ J/s}}$$

21.31

Basis: 1 minute

$$\text{KE} = (1/2) mv^2$$

$$v = \frac{500,000 \text{ g}}{\text{min}} \left| \frac{1 \text{ cm}^3}{1.15 \text{ g}} \right| \left| \frac{4}{\pi(5)^2 \text{ cm}^2} \right| = 22,143 \text{ cm/min}$$

$$\text{KE} \approx \frac{1}{2} \left| \frac{500 \text{ kg}}{\text{min}} \right| \left(\left| \frac{22,143 \text{ cm}}{\text{min}} \right| \right)^2 \left| \frac{1(\text{J})(\text{s}^2)}{1(\text{kg})(\text{m}^2)} \right| \left(\left| \frac{1 \text{ min}}{60 \text{ s}} \right| \right)^2 \left(\left| \frac{1 \text{ m}}{100 \text{ cm}} \right| \right)^2 = \boxed{6810 \text{ J}}$$

21.32

Basis: 1 lb_m H₂O

$$\text{KE} = 1/2 mv^2$$

$$\text{KE} = \frac{1}{2} \left| \frac{1 \text{ lb}_m}{1} \right| \left(\left| \frac{10 \text{ ft}}{\text{s}} \right| \right)^2 \left| \frac{(\text{lb}_f)(\text{s}^2)}{32.2 (\text{lb}_m)(\text{ft})} \right| = \boxed{1.55 (\text{ft})(\text{lb}_f)}$$

Solutions Chapter 21

21.33

The density of air at 27°C and 1 atm is $\rho = \frac{(p)(MW)}{(RT)}$

$$\rho = \frac{101.3 \text{ kPa}}{1 \text{ kg mol air}} \left| \frac{29 \text{ kg air}}{8.314(\text{kPa})(\text{m}^3)} \right| \left| \frac{(\text{kg mol})(\text{K})}{300 \text{ K}} \right| = 1.18 \text{ kg/m}^3$$

$$\text{Power} = \frac{1}{2} \dot{m} v^2 = \frac{1}{2} (\rho A v) v^2 = \frac{1}{2} \rho A v^3$$

Assume air flow through the windmill is equivalent to the average flow in a pipe of diameter 15m.

$$v = \frac{20 \text{ mi}}{\text{hr}} \left| \frac{1.61 \times 10^3 \text{ m}}{1 \text{ mi}} \right| \left| \frac{1 \text{ hr}}{3600 \text{ s}} \right| = 8.94 \text{ m/s}$$

$$\text{Power} = \left(\frac{1}{2} \right) \left| \frac{1.18 \text{ kg}}{\text{m}^3} \right| \left(\left| \frac{\pi \left(\frac{15 \text{ m}}{2} \right)^2}{\text{s}} \right| \right) \left(\left| \frac{8.94 \text{ m}}{\text{s}} \right| \right)^3 \left| \frac{1(\text{s}^2)\text{J}}{1(\text{kg})(\text{m}^2)} \right| \left| \frac{(\text{s})(\text{W})}{1 \text{ J}} \right| \left| \frac{1 \text{ kW}}{1000 \text{ W}} \right| = \boxed{74.46 \text{ kW}}$$

$$\text{Electrical energy} = (74.46)(0.30) = \boxed{22.3 \text{ kW}}$$

21.34

Basis: 1 lb_m of vehicle

$$\text{a. } \frac{25,000 \text{ mi}}{\text{hr}} \left| \frac{1 \text{ hr}}{3600 \text{ s}} \right| \left| \frac{5280 \text{ ft}}{1 \text{ mi}} \right| = 36,600 \text{ ft/s}$$

(continued)

Solutions Chapter 21

$$K.E. = \frac{1}{2} \left| \frac{1.34 \times 10^9 \text{ ft}^2}{\text{s}^2} \right| \left| \frac{1 \text{ lb}_m}{\text{lb}_c} \right| \frac{1}{g_c} = 2.08 \times 10^7 \frac{(\text{ft})(\text{lb}_f)}{\text{lb}_m}$$

$$K.E. = \frac{2.08 \times 10^7 (\text{ft})(\text{lb}_f)}{\text{lb}_m} \left| \frac{1 \text{ Btu}}{778 (\text{ft})(\text{lb}_f)} \right| = \boxed{2.68 \times 10^4 \text{ Btu} / \text{lb}_m}$$

b. Heat capacity of, say, 1 Btu/(lb) (°F) gives

$$\frac{1 \text{ Btu}}{(\text{lb})(^\circ\text{F})} \left| \frac{20^\circ\text{F}}{1} \right| = 20 \text{ Btu} / \text{lb}_m.$$

Essentially all the energy must be transferred to the surroundings

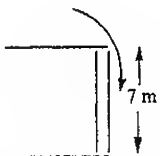
21.35

Basis: 2 kg mass

$$PE = mgh = \frac{12 \text{ kg}}{1} \left| \frac{9.80 \text{ m}}{\text{s}^2} \right| \left| \frac{25 \text{ m}}{1} \right| \left| \frac{1(\text{J})(\text{s}^2)}{1(\text{kg})(\text{m}^2)} \right| = \boxed{2940 \text{ J}}$$

21.36

Filled reservoir



Assume 7 meters is a constant level difference hence $h = 7\text{m}$

For one-half of the complete cycle (6 hours):

Solutions Chapter 21

$$m = \rho Ah = \frac{10^3 \text{ kg}}{\text{m}^3} \left| \frac{23 \text{ km}^2}{1} \right| \left| \frac{7 \text{ m}}{1} \right| \left| \frac{\left(\frac{10^3 \text{ m}}{1 \text{ km}} \right)^2}{1} \right| = 1.61 \times 10^{11} \text{ kg}$$

$$\Delta(PE) = \frac{1.61 \times 10^{11} \text{ kg}}{1} \left| \frac{9.80 \text{ m}}{\text{s}^2} \right| \left| \frac{7 \text{ m}}{1} \right| \left| \frac{1 \text{ J}}{(1 \text{ kg})(\text{m}^2)} \right| \frac{1}{\text{s}^2} = 1.10 \times 10^{13} \text{ J}$$

For a complete cycle:

$$\frac{2 \left| \frac{1.10 \times 10^{13} \text{ J}}{1} \right| \left| \frac{0.85}{1} \right|}{370 \text{ min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = 4.23 \times 10^8 \text{ J/s}$$

$$\text{or } \boxed{5.06 \times 10^8 \text{ W}}$$

21.37

Relative to the reference values in the steam tables and the CD:

- (a) $\boxed{U = 3528 \text{ kJ/kg}}$ (from the steam tables)
- (b) The quality is 0.13% and $\boxed{U = 1213 \text{ kJ/kg}}$ from the steam tables
- (c) At 100°C and 1000 kPa , U of the liquid is about $\boxed{U \approx 532 \text{ kJ/kg}}$ from the steam table

21.38

The heat capacity of a monoatomic ideal gas is $\frac{5}{2}R$, and the heat capacity at constant

$$\text{volume is: } \frac{5}{2}R - R = \frac{3}{2}R$$

(continued)

Solutions Chapter 21

You can show that $C_p = C_v + R$

$$C_p = \left(\frac{\partial \hat{H}}{\partial T} \right)_p = \left[\frac{\partial \hat{U} + \partial(p\hat{V})}{\partial T} \right]_p = \left(\frac{\partial \hat{U}}{\partial T} \right)_p + p \left(\frac{\partial \hat{V}}{\partial T} \right)_p$$

For the ideal gas $\hat{U}$ is a function of T only (not of p or $\hat{V}$) so that

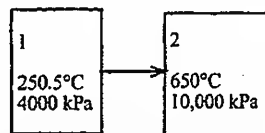
$$\left(\frac{\partial \hat{U}}{\partial T} \right)_p = \left(\frac{\partial \hat{U}}{\partial T} \right)_v = C_v$$

$$p \left(\frac{\partial \hat{V}}{\partial T} \right)_p = p \left(\frac{R}{p} \right) = R$$

$$\Delta U = \int C_v dT = (3/2 R)(50) = \boxed{624 \text{ J}}$$

21.39

Basis: 1 kg steam



$\Delta U = \Delta H - \Delta pV$ or use U values directly from SI tables or computer code.

Data here taken from the steam tables.

Solutions Chapter 21

	State 1 (assumed saturated)	State 2 (superheated)
T	250.5°C (523.5 K) 482°F 4000 kPa abs.	650°C (923 K) 1202°F 10,000 kPa abs.
p	580 psia	1450 psia
$\hat{V}$	0.498 m ³ /kg	0.04117 m ³ /kg
ΔU	2602 kJ/kg	3338 kJ/kg
ΔH (ref. satd liquid at 0°C)	2801 kJ/kg	3742 kJ/kg

21.40

Internal energy is the energy contained in the material of a system because of its molecular arrangement. Heat is energy that flows between the system and the surroundings because of a temperature gradient. Therefore they are not the same class of energy.

21.41

$$\Delta H = \Delta U + \Delta(pV)$$

When a liquid vaporizes $\Delta(pV)$ adds to ΔU .

21.42

ΔH and ΔU are zero because ΔH and ΔU are point (state) functions (variables).

21.43

None. The initial and final states for U and H are the same.

Solutions Chapter 21

21.44

The energy balance is $\Delta E = \Delta U + \Delta PE + \Delta KE = Q + W$

	Q	W	ΔE	ΔU
(a)	>0	0	>0	>0
(b ₁)	0	>0	>0	>0
(b ₂)	0	>0	>0	>0
(c)	0	>0	>0	>0

21.45

Basis: 10 lb mol ideal gas

(a) Use $pV = nRT$

$$\Delta(p\hat{V}) = \Delta(RT)$$

$$(1) \frac{10 \text{ lb mol}}{1 \text{ lb mol}} \left| \frac{359 (\text{ft})^3}{1100 \text{ atm}} \right| \frac{1 \text{ atm}}{14.7 \text{ atm}} \frac{500^\circ\text{R}}{492^\circ\text{R}} = 36.5 (\text{ft})^3 @ 100 \text{ atm}, 40^\circ\text{F}$$

$$(2) \frac{100 \text{ atm}}{500^\circ\text{R}} \left| \frac{900^\circ\text{R}}{500^\circ\text{R}} \right| = 180 \text{ atm}$$

$$(3) \Delta H = (\hat{H}_2 - \hat{H}_1) 10 = 10 [300 + 8.0 (440) - (300 + 8.0 (40))] = 32,000 \text{ Btu}$$

(b) The equation for $\hat{H}$ is based on the reference conditions where $\hat{H} = 0$.

$\hat{H} = 0$ when $300 = -8T$ or $T_{\text{ref}} = -37.5^\circ\text{F} = -38.5^\circ\text{C}$. U should have the same reference temperature.

$$\Delta \hat{U} = \Delta \hat{H} - \Delta(p\hat{V}) = \Delta \hat{H} - \Delta RT \text{ for an ideal gas}$$

Solutions Chapter 21

Change units for $\hat{H}$:

$$\text{First term: } \frac{300 \text{ Btu}}{1 \text{ lb mol}} \left| \frac{1 \text{ lb mol}}{454 \text{ g mol}} \right| \frac{1055 \text{ J}}{\text{Btu}} = \frac{697 \text{ J}}{\text{g mol}} \quad T_{\text{ref}} = 1.8T_c + 32$$

$$\text{Second term: } \frac{8.0 \text{ Btu}}{(\text{lb mol})(^\circ\text{F})} \left| \frac{1055 \text{ J}}{\text{Btu}} \right| \frac{1 \text{ lb mol}}{454 \text{ g mol}} \left| \frac{(1.8T_c + 32)^\circ\text{F}}{1} \right| = (33.5T_c + 595) \frac{\text{J}}{\text{g mol}}$$

$$\hat{H}_{\text{ref}} = 0$$

$$\Delta H = H_T - H_{\text{ref},T} = H_T \quad \Delta RT = (RT)_T - (RT)_{\text{ref}} \quad (T \text{ is absolute})$$

$$\Delta U = 697 + 595 + 33.5 T_c - R(T_{\text{ABS}} - T_{\text{ABS,REF},T})$$

$$T_{\text{ABS}} = T_c + 273$$

$$T_{\text{ABS,REF},T} = -38.5 + 273$$

$$\Delta U = 1292 + 33.5 T_c - 8.314 (T_c + 38.5) = 1215 + 31.5 T_c$$

21.46

Use the same reference state, so that

$$\Delta \hat{H} = \Delta \hat{U} + \Delta(p\hat{V})$$

For one mole of an ideal gas: $p\hat{V} = RT$

$$\Delta \hat{U} = \Delta \hat{H} - \Delta RT$$

$$= 6.05 \times 10^5 \frac{\text{J}}{\text{kg mol}} - \frac{8.314 \text{ J}}{(\text{g mol})(\text{K})} \left| \frac{10^3 \text{ g mol}}{1 \text{ kg mol}} \right| [(100 + 273) - (273)] \text{K}$$

$$= 6.05 \times 10^5 - 8.314 \times 10^5 = -2.26 \times 10^5 \text{ J/kg mol}$$

Solutions Chapter 21

21.47

(a)	T	(f)	F
(b)	F	(g)	F
(c)	F	(h)	F
(d)	T	(i)	T
(e)	F	(j)	T

21.48

(a)	F	(f)	T	(k)	T
(b)	F	(g)	F	(l)	F
(c)	F	(h)	T	(m)	T
(d)	T	(i)	F	(n)	T
(e)	T	(j)	F		

Solutions Chapter 22

22.1

All of them.

22.2

(a)

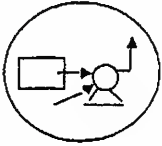
pump



system is the pump. Open, steady state.

$\dot{Q}$	$\dot{W}$	ΔU	ΔH	ΔPE	ΔKE
Very little	Yes	No	Yes(flow)	No	No

(b)



system is the pump and motor. Open, steady state

A little	Yes	No	Yes	No	No
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(c)

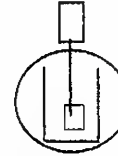


System is the ice. Closed, unsteady state.

Yes	No	Yes	Yes	No	No
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Solutions Chapter 22

(d)



system is the mixer and solution. The process is closed, unsteady state.

Possibly Yes	Yes	Yes	Yes	No	No
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22.3

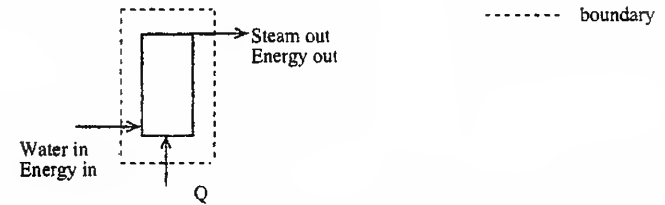
a. System: can and liquid $Q = 0, W \neq 0$

b. System: motor $Q = 0, W \neq 0$ But motor may get hot.

c. System: pipe and water $Q = 0, W \neq 0$

22.4

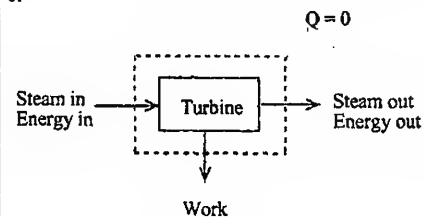
a.



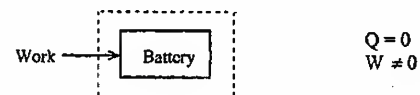
(continued)

Solutions Chapter 22

b.



c.



22.5

No. The energy balance is $Q + W = \Delta U$, and for $Q = 0$ and since $\Delta U = 0$ for an isothermal process $W = 0$.

22.6

This is an unsteady state closed process

Basis: 1 lb water

Data from the CD

Initial Conditions

$T = 327.8^\circ\text{F}$

Final conditions

$T = 327.8^\circ\text{F}$

Solutions Chapter 22

$p = 100 \text{ psia}$

$\hat{V} = 0.018 \text{ ft}^3/\text{lb}$ for liquid and 4.435 for vapor $\hat{V} = 4.435$

$\hat{H} = 298.475 \text{ Btu/lb}$

$\hat{U} = 298.146 \text{ Btu/lb}$

$V = 4.435 \text{ ft}^3$

$V = 4.435 \text{ ft}^3$

At the final conditions the water is saturated vapor

$H = 1187.48 \text{ Btu/lb}$

$U = 1105.46 \text{ Btu/lb}$

$T = 327.75^\circ\text{F}$

$p = 100 \text{ psia}$ still

$\Delta H = 1187.48 - 298.475 = \boxed{889.0 \text{ Btu/lb}}$

$\Delta U = 1105.46 - 298.146 = \boxed{807.3 \text{ Btu/lb}}$

The energy balance is

$\Delta U = Q + W$

$W = 0$ (fixed container)

$Q = \Delta U = \boxed{807.3 \text{ Btu/lb}}$

22.7

Closed unsteady state system

$Q + W = \Delta U$

$60 + W = 220$

$\boxed{W = 160 \text{ Btu}}$ (work done on the system)

Solutions Chapter 22

22.8

Closed unsteady state system

$$Q + W = \Delta U$$

$$\text{In kJ: } (30-5) + 0.5 = U_f - 10 \quad U_f = 35.5 \text{ kJ}$$

22.9

Closed unsteady state system

$$Q + W = \Delta U \quad Q = 0$$

$$W = \Delta U = C_v \Delta T$$

$$W = \frac{(100 \text{ W})(5 \text{ hr})}{1000 \text{ W}} \left| \frac{1 \text{ kW}}{1 \text{ kW}} \right| \frac{3.6 \times 10^3 \text{ kJ}}{1 \text{ kW}} = 1.8 \times 10^3 \text{ kJ}$$

$$\text{mols of air} = n = \frac{pV}{RT} = \frac{(100 \text{ kPa})(100 \text{ m}^3)}{303 \text{ K}} \left| \frac{(\text{kg mol})(\text{K})}{(8.314)(\text{kPa})(\text{m}^3)} \right| = 3.97 \text{ kg mol}$$

$$1.8 \times 10^3 = 30(3.97)(T - 30) \quad T = 45^\circ\text{C}$$

22.10

Closed unsteady state process

$$Q + W = \Delta U + \Delta(\text{PE})$$

Solutions Chapter 22

Ignore change in center of mass of the air

$$Q = 0 \text{ assumed}$$

$$\Delta U = 0 \text{ assumed (to get maximum elevation)}$$

$$W = 100 \text{ J}$$

$$100 = \Delta(\text{PE}) = mg\Delta h = (0.990 \text{ kg})(9.80 \text{ m/s}^2) \Delta h \text{ (m)}$$

$$\Delta h = 10.3 \text{ m}$$

22.11

Closed unsteady state system

Use the CD to get data

Basis: 4 kg steam

Initial Conditions

Final Conditions

$$\text{Given: } T = 500\text{K} \\ p = 700 \text{ kPa}$$

$$\text{Given: } T = 400\text{K} \\ \text{Known: } \hat{V} = 0.320 \text{ m}^3/\text{kg}$$

$$\text{Look up: } \hat{V} = 0.320 \text{ m}^3/\text{kg} \\ \hat{H} = 2903.94 \text{ kJ/kg} \\ \hat{U} = 2680.51 \text{ kJ/kg}$$

Look up (2 phase system) the quality (trial and error on the CD): $x = 0.437$

$$\text{Calculate } V = 0.320(4) = 1.280 \text{ m}^3/\text{kg}$$

$$\hat{H} = 1486.81 \text{ kJ/kg} \\ \hat{U} = 1408.23 \text{ kJ/kg} \\ p = 245.77 \text{ kPa}$$

$$\hat{Q} + \hat{W} = \Delta \hat{U} \quad \hat{W} = 0$$

$$Q = (1408.23 - 2680.51)(4) = (-1272.3)(4) = -5,089 \text{ kJ}$$

If you do not use the CD, $\Delta \hat{U} = \Delta \hat{H} - (\Delta p \hat{V})$.

22.12

Closed, unsteady state process

Initial conditions $V = 1 \text{ ft}$ saturated dry satd. steam (the basis)

Look up

$\hat{V} = 33.610 \text{ ft}^3/\text{lb}$

$\hat{H} = 1145.72 \text{ Btu/lb}$

$\hat{U} = 1073.96 \text{ Btu/lb}$

$p = 11.548 \text{ psia}$

Calculate the lb of steam

$$m = \frac{1 \text{ lb}}{33.610 \text{ ft}^3} \left| \frac{1 \text{ ft}^3}{1} \right| = 0.02975 \text{ lb}$$

$Q + W = \Delta U$

a. $W = 0$ (fixed boundary)

$Q = \Delta U$

b&c. $\Delta U = U_2 - U_1 = (1077.48)(0.02975) - (1073.96)(0.02975) = 0.105 \text{ Btu} = Q$

d. The volume of the second tank is $V_{\text{final}} = (392.713)(0.02975) = 11.68$
 $V_2 = 11.68 - 1 = 10.68 \text{ ft}^3$

Final conditions

$V = 1 \text{ ft (known)} + V_2$

At $p = 1 \text{ psia}$ $T = 200^\circ\text{F}$. The water is vapor

From the steam tables:

$\hat{H} = 1150.15 \text{ Btu/lb}$

$\hat{U} = 1077.48 \text{ Btu/lb}$

$\hat{V} = 392.713 \text{ ft}^3/\text{lb}$

22.13

Closed unsteady state process for each stage.

$Q + W = \Delta U$ overall

Calculate the moles of gas:

a. $n = \frac{pV}{RT} = \frac{(1 \text{ atm})(0.387 \text{ ft}^3)(\text{lb mol})(^\circ\text{R})}{(530^\circ\text{R})(0.7302)(\text{ft}^3)(\text{atm})} = 1 \times 10^{-3} \text{ lb mol}$ (Basis)

Known values	A	B	C	D
p (atm)	1	1	10	10
T ($^\circ\text{F}$)	170 (630 $^\circ\text{R}$)	70 (530 $^\circ\text{R}$)	70 (530 $^\circ\text{R}$)	823 (1283 $^\circ\text{R}$)
n (lb mol)	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
V	?	0.387	?	?

For an ideal gas, $C_v = 5/2 R$ (has to be looked up or calculated) and U and H are functions of T only

Also, $\Delta(pV) = \Delta(nRT)$

Calculate some of the missing values

$$V_A = \frac{(1 \times 10^{-3})(0.7302)(630)}{1} = 0.460 \text{ ft}^3$$

$$V_C = \frac{(1 \times 10^{-3})(0.7302)(530)}{10} = 0.0387 \text{ ft}^3$$

b. $V_D = \frac{(1 \times 10^{-3})(0.7302)(1283)}{10} = 0.0937 \text{ ft}^3$

(continued)

Solutions Chapter 22

The work for each stage will be assumed to be $\int p dV$ (ideal process)

W_{AB} (constant pressure process)

$$\begin{aligned} \text{c. } W &= -\int p dV = -p_{AB}(V_B - V_A) \\ &= -1 \text{ atm} \left| \frac{(0.387 - 0.460) \text{ ft}^3}{(\text{atm})(\text{ft}^3)} \right| \frac{2.72 \text{ Btu}}{(\text{atm})(\text{ft}^3)} = \boxed{-0.199 \text{ Btu}} \end{aligned}$$

W_{BC} (isothermal process)

$$\begin{aligned} \text{d. } W &= -\int p dV = -\int_{0.387}^{0.0387} \frac{nRT}{V} dV = -nRT \int_{0.387}^{0.0387} \frac{dV}{V} = -nRT [\ln V]_{0.387}^{0.0387} \\ &= -(1 \times 10^{-3})(1.987)(530)(\ln 0.1) = \boxed{2.42 \text{ Btu}} \end{aligned}$$

W_{CD} (constant pressure process)

$$\text{e. } W = -\int p dV = -p_{CD}(V_D - V_C) = -(10)(0.0937 - 0.0387) = \boxed{-0.550 \text{ Btu}}$$

W_{DA} (ideal adiabatic process)

$$W = -\int p dV = -\int \frac{nRT}{V} dV \quad \text{However, both } T \text{ and } V \text{ vary.}$$

Instead use

$$Q + W = \Delta U \quad Q = 0 \quad R = 1.987 \text{ Btu}/(\text{lb mol}) (\text{°R})$$

$$\text{f. } W = \Delta U = nC_v \Delta T = (10^{-3}) \left(\frac{5R}{2} \right) (630 - 1283) = \boxed{-3.243 \text{ Btu}}$$

$$\text{g. } W_{\text{overall}} = 0.199 + 0.891 - 0.550 - 3.243 = \boxed{-1.74 \text{ Btu}}$$

Solutions Chapter 22

$$\text{h. } \Delta H = 0 \quad (\text{a cycle})$$

$$\text{i. } \text{For the overall process } Q + W = \Delta U. \text{ Because of the cycle, } \Delta U = 0, \text{ and thus } Q = -W = \boxed{1.74 \text{ Btu}}$$

22.14

A closed, unsteady state system comprised of 2 tanks. Get the steam properties from the CD.
Basis: 1 lb steam.

State 1	State 2
$m = 1 \text{ lb}$	$m = 1 \text{ lb}^*$
$p = 600 \text{ psia}$	$p = 330.45 \text{ psia}$
$\hat{V} = 0.795 \text{ ft}^3/\text{lb}$	$\hat{V} = 1.590 \text{ ft}^3/\text{lb}$
$T = 500^\circ\text{F} (960^\circ\text{R})$	$T = 500^\circ\text{F} (960^\circ\text{R})^*$
$\dot{U} = 1128.19 \text{ Btu/lb}$	$\dot{U} = 1157.03 \text{ Btu/lb}$
$\dot{H} = 1215.97 \text{ Btu/lb}$	$\dot{H} = 1253.98 \text{ Btu/lb}$
$V_1 = 0.795 \text{ ft}^3$	$V_2 = 2V_1 = 1590 \text{ ft}^3^*$

* used to get state 2 properties

The closed system is $Q + W = \Delta U$

$$\Delta U = 1157.03 - 1128.19 = \boxed{28.84 \text{ Btu/lb}}$$

$$W = 0 \text{ (fixed boundary)}$$

$$Q = \Delta U = \boxed{28.84 \text{ Btu/lb}}$$

$$\Delta H = 1253.98 - 1215.97 = \boxed{38.01 \text{ Btu/lb}}$$

Solutions Chapter 22

22.15

No. For each path $Q + W = \Delta U$, and for the cycle 1 to 2 and back $\Delta U = 0$. Addition gives

$$(Q_A + W_A) + (Q_B + W_B) = \Delta U_{1-2} + \Delta U_{2-1} = 0$$

$$(Q_A + Q_B) = -(W_A + W_B)$$

Note: The equations in the problem used a different sign for W . A similar analysis applies to the second equation in the problem.

22.16

A closed steady-state system.

The cooling at the maximum efficiency is

$$\frac{0.695 \text{ kW}}{(1 \text{ kW})(s)} \left| \frac{0.948 \text{ Btu}}{(1 \text{ kW})(s)} \right| \frac{3600s}{1 \text{ hr}} = 2372 \text{ Btu/hr}$$

not 5500 Btu/hr.

The main question with the advertisement is: where does the energy go that is removed from the room if the unit does not require outside venting?

22.17

A closed steady-state system

$$\dot{Q} + \dot{W} = \Delta \dot{U} = 0$$

$$\dot{Q} = -\dot{W} \quad Q \text{ is negative (heat loss)}$$

Solutions Chapter 22

$$\dot{Q} = -\frac{2050 \times 10^3 \text{ J}}{\text{hr}} \left| \frac{1 \text{ hr}}{3600 \text{ s}} \right| \frac{10^3 \text{ kW}}{1(\text{J})(s)} = -0.57 \text{ kW}$$

$$\dot{W} = 0.57 \text{ kW}$$

22.18

A closed steady-state system

$$\dot{Q} + \dot{W} = \Delta \dot{U} = 0 \quad \dot{Q} = -\dot{W}$$

$$\dot{W} = \frac{0.25 \text{ hp}}{1 \text{ hp}} \left| \frac{0.7068 \left(\frac{\text{Btu}}{\text{s}} \right)}{1 \text{ min}} \right| \frac{60 \text{ s}}{1 \text{ min}} = 10.6 \text{ Btu/min} \quad \dot{Q} = -10.6 \text{ Btu/min}$$

22.19

Open system, unsteady-state. The system is the volume containing 1 lb of H_2O at 27°C (liquid). At the end of the process the system contains nothing. The water leaving is at 100°C because the atmospheric pressure is 760 mm Hg.

$$Q + W = \Delta H \quad W = 0$$

$$Q = \Delta H \approx \hat{H}_{\text{out}}(1) - \hat{H}_{\text{in}}(0)$$

The reference temperature for enthalpy is 0°C but the water is at

$$27^\circ\text{C}, \hat{H}_{\text{out}} = \hat{H}_{100^\circ\text{C}} - \hat{H}_{27^\circ\text{C}}$$

$$Q = (1 \text{ kg}) (2675.6 - 111.7) \text{ kJ/kg} = \boxed{2558 \text{ kJ}}$$

22.20

Basis: 1 lb H₂O at 212°F, 1 atm

Data from the CD

	Initial (liquid)	Final (vapor)
$\hat{U}$	180.182 Btu/lb	1077.40 Btu/lb
$\hat{H}$	180.226 Btu/lb	1150.29 Btu/lb
$\hat{V}$	0.017 ft ³ /lb	26.773 ft ³ /lb

$$p = 1.00 \text{ atm}$$

Non-flow process (unsteady-state)

$$Q + W = \Delta U$$

$$\Delta U = (1 \text{ lb})(1077.40 - 180.182) \text{ Btu/lb} = 897.22 \text{ Btu}$$

$$W = -\int p dV = -(1 \text{ atm})(26.773 - 0.017) \text{ ft}^3/\text{lb} (2.72) \text{ Btu/(atm)(ft}^3\text{)}$$

$$= -72.78 \text{ Btu}$$

$$Q = 897.22 - (-72.78) = \boxed{970.0 \text{ Btu}}$$

$$\Delta H = 1150.29 - 180.226 = \boxed{970.0 \text{ Btu}}$$

Flow process (unsteady-state)

$$\Delta U = Q + W - \Delta H$$

Assume the volume of the system is fixed at $V = 0.017 \text{ ft}^3$ and that $W = 0$. Also assume that nothing is left in the system after the water evaporates.

$$\Delta U = \hat{U}_{\text{final}}(0) - \hat{U}_{\text{initial}}(1) = -180.182 \text{ Btu}$$

$$\Delta H = \hat{H}_{\text{out } 1212^\circ\text{F}}(1) - \hat{H}_{\text{in}}(0) = 1150.29 \text{ Btu}$$

$$Q = \Delta U + \Delta H = -180.182 + 1150.29 = \boxed{970.1 \text{ Btu}}$$

22.21

Treat the system (the cylinder) as an unsteady state flow system.

$$\Delta U = Q + W - \Delta H$$

$$W = 0 \quad Q = 0$$

$$U_{i_1} - U_{i_1} = -(H_{\text{out}} - H_{\text{in}})$$

$$\hat{U}_{i_2} = \hat{U}_{1,40 \text{ atm}}$$

 n_f = final moles in cylinder

$$\hat{U}_{i_1} = \hat{U}_{298\text{K}, 1 \text{ atm}}$$

 n_i = initial moles in cylinder

$$\hat{H}_{\text{out}} = 0$$

$$\hat{H}_{\text{in}} = \hat{H}_{298 \text{ K}, 50 \text{ atm}}$$

Let the reference temperature be T_R that makes $\hat{H}_R = 0$. Ignore the effect of pressure on the values of $\hat{U}$ and $\hat{H}$.

$$\hat{H}_{\text{in}} = \hat{H}_R + C_p(T_{\text{in}} - T_R) \quad \hat{H}_R = 0$$

$$\frac{\Delta U}{\text{in}} \quad \text{out}$$

$$U_{i_2} - U_{i_1} = n_f \hat{U}_{i_2} - n_i \hat{U}_{i_1} = (n_f - n_i) \hat{H}_{\text{in}} - 0$$

(continued)

Solutions Chapter 22

$$n_f [C_v (T - T_R) - RT_R] - n_i [C_v (T_{in} - T_R) - RT_R] = (n_f - n_i) [C_p (T_{in} - T_R)]$$

$$= (n_f - n_i) [(C_v + R)(T_{in} - T_R)]$$

Multiply all of the terms out to get (note terms with T_R cancel):

$$n_f C_v T = n_f C_v T_{in} + n_f RT_{in} - n_i RT_{in} \quad C_v = C_p - R$$

Insert $pV = nRT$ to get n_i and n_f

$$\frac{R}{C_v} = \frac{2}{5} \text{ for diatomic gas}$$

The equations reduce to

$$n_f C_v T = n_f C_v T_{in} + n_f RT_{in} - n_i RT_{in}$$

$$\frac{T}{T_{in}} = \left[1 + \frac{R}{C_v} - \frac{p_i}{p_f} \frac{T}{T_{in}} \frac{R}{C_v} \right]$$

$$\frac{T}{298} = \left[1 + \frac{2}{5} - \left(\frac{1}{40} \right) \left(\frac{T}{298} \right) \left(\frac{2}{5} \right) \right]$$

$$T = 417 \text{ K}$$

Solutions Chapter 22

22.22

The tank is an open unsteady state system. f stands for final, i for initial, in for in, m for mass in lb.

Data:

at 29.1°F and 50 psia

at 14.7 psia saturated (212°F)

1179.39	$\hat{H}$ Btu/lb	1150.26
1099.60	$\hat{U}$ Btu/lb	1077.37
8.653	$\hat{V}$ ft ³ /lb	26.818

$$\Delta U = Q + W - \Delta H \quad W = 0 \quad Q = 0 \quad H_{out} = 0$$

$$\Delta U = -\Delta H$$

$$n_f \hat{U}_f - m_i \hat{U}_i = (m_f - m_i) \hat{H}_m - 0$$

$$V = 50 \text{ ft}^3 \text{ so } m_f = \frac{50}{8.653} = 5.78 \text{ lb}$$

$$m_i = \frac{50}{26.818} = 1.86 \text{ lb}$$

$$5.78(\hat{U}_f) - 1.86(1077.37) = (5.78 - 1.86) 1179.39$$

$$\hat{U}_f = 1146.56 \text{ Btu/lb at 50 psia}$$

$$T_f = 411^\circ\text{F} \quad (\text{superheated})$$

Solutions Chapter 22

22.23

Basis: interval of 1 hr (1800 gal or (1800)(8.33) = 15,000 lb water)

Open, unsteady state system. System is storage tank plus the water lines.

$$\Delta U = Q + W - (\Delta H + \Delta PE)$$

Data: 35°F saturated water

$$\hat{U} \text{ Btu/lb} \quad 3.025$$

$$\hat{H} \text{ Btu/lb} \quad 3.025$$

$$\hat{V} \text{ ft}^3/\text{lb} \quad 0.016$$

Ignore the water in the lines initially and finally assume no change. Also ignore the increased depth of the water in the storage tank.

$$\Delta PE = \frac{100 \text{ ft}}{1} \left| \frac{15,000 \text{ lb}}{1} \right| \left| \frac{\text{g}}{g_c} \right| \left| \frac{1 \text{ Btu}}{7.7816 \times 10^3 (\text{ft})(\text{lb}_f)} \right| = 1928 \text{ Btu}$$

$$Q = \frac{1000 \text{ Btu}}{\text{min}} \left| \frac{60 \text{ min}}{\text{hr}} \right| \sim 5000 = 5.5 \times 10^4 \text{ Btu}$$

$$H_{35^\circ\text{F}, \text{in}} = \frac{15,000 \text{ lb}}{1} \left| \frac{3.025 \text{ Btu}}{\text{lb}} \right| = 45,380 \text{ Btu}$$

$$H_{\text{out}} = 0 \text{ (no flow out)}$$

$$U_{i_2} = 15,000 \hat{U}_T$$

$$U_{i_1} = 0 \text{ (no water in the tank)}$$

Solutions Chapter 22

$$W = \frac{5 \text{ hp}}{1} \left| \frac{1 \text{ hr}}{1} \right| \left| \frac{0.30}{1} \right| \left| \frac{2.545 \times 10^3 \text{ Btu}}{1 \text{ hph}} \right| = 3,820 \text{ Btu}$$

The balance in Btu is

$$15,000 \hat{U}_T - 0 = 5.5 \times 10^4 + 3,820 - (0 - 45,380) - 1928$$

$$\hat{U}_T = 6.82 \text{ Btu/lb}$$

From the steam tables for saturated water this value of $\hat{U}_T$ corresponds to 39°F. A good solution would also be obtained by letting $\Delta U = C_v \Delta T \cong C_p \Delta T$ or $3.8 = (1) \Delta T$ so that $T = 3.8 + 35 \cong 39^\circ\text{F}$.

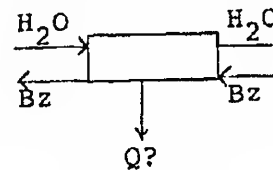
22.24

The general energy balance is

$$\Delta E = Q + W - \Delta[(\hat{H} + \hat{K}E + \hat{P}E) m]$$

$$(1) \quad (2) \quad (3) \quad (4) \quad (5) \quad (6)$$

- (a) (1) $\Delta E = 0$ steady state flow process, one overall system (You can also pick two system, one the H_2O and one the benzene).



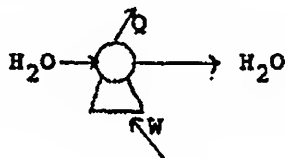
(continued)

Solutions Chapter 22

- (2) Q is the net overall heat transfer to and from the heat exchanger with the surroundings.

It is essentially 0 if exchanger is well insulated. If you pick 2 systems, Q is the heat transfer between the benzene and the H_2O , and is not 0.

- (3) $W = 0$ no mechanical work in the process
- (4) $\Delta H \neq 0$ for all streams
- (5) $\Delta KE = 0$ negligible KE change
- (6) $\Delta PE = 0$ level exchanger assumed. $Q = \Delta H$
- (b) (1) $\Delta E = 0$ steady state process
- (2) Q not zero as isothermal



- (3) W retain
- (4) $\Delta H \neq 0$ the pressure changes even if T is constant
- (5) $\Delta KE = 0$ pipe diameter remains the same, and the flow rate is the same
- (6) $\Delta PE = 0$ level pump lines
- $Q + W = \Delta H$

Solutions Chapter 22

22.25

Unknowns

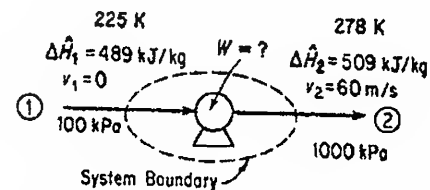
$\dot{F}$
 $\dot{P}$
 $\dot{V}$
 $\dot{S}$
 $\dot{Q}$
 T_v
 x_p

Relationships (R)

- (1) $F = P + V$
 (2) $0.05F = x_p P$
 (3) $F\hat{H}_f + S\Delta H_s = V\hat{H}_v + P\hat{H}_p$
 (4) $S\Delta H_s = \dot{Q}$
 (5) $\dot{Q} = UA(T_s - T_v)$

Yes, two measurements must be made to balance the unknowns and the relationships. If x_p and T_v are measured: solve (R5) for $\dot{Q}$. (R4) for $\dot{S}$ substitute (R2) and (R1) in (R3) and solve for F . Use (R2) to calculate P and (R1) to calculate $\dot{V}$. Note that measuring T_v and S is not satisfactory because this combination eliminates either (R4) or (R5) as an independent relationship. Also note that if you neglect the vapor pressure of the organic, you can set $T_v = 212^\circ\text{F}$.

22.26



(continued)

Solutions Chapter 22

Steps 1, 2, 3, and 4:

Figure P22.27 shows the known quantities. No reaction occurs. The process is clearly a flow process (open system). Assume that the entering velocity of the air is zero.

Step 5:

Basis: 100 kg of air = 1 hr

Steps 6 and 7:

Simplify the energy balance (only one component exists):

$$\Delta E = Q + W - \Delta[(\hat{H} + \hat{K}E + \hat{P}E)m]$$

- (1) The process is in the steady state, hence $\Delta E = 0$.
- (2) $m_1 = m_2 = m$.
- (3) $\Delta(\hat{P}E)(m) = 0$.
- (4) $Q = 0$ by assumption (Q would be small even if the system were not insulated).
- (5) $v_1 = 0$ (value is not known but would be small).

The result is

$$W = \Delta[(\hat{H} + \hat{K}E)m] = \Delta H + \Delta KE$$

We have one equation and one unknown, W . ΔKE and ΔH can be calculated, hence the problem has a unique solution.

Solutions Chapter 22

Steps 7, 8, and 9

$$\Delta H = \frac{(509 - 489)\text{kJ}}{\text{kg}} \left| \frac{100 \text{ kg}}{1} \right| = 2000 \text{ kJ}$$

$$\Delta KE = \frac{1}{2} m(v_2^2 - v_1^2)$$

$$= \left(\frac{1}{2} \right) 100 \text{ kg} \left| \frac{(60 \text{ m}^2/\text{s}^2)}{1000(\text{kg})(\text{m}^2/\text{s}^2)} \right| = 180 \text{ kJ}$$

$$W = (2000 + 180) = 2180 \text{ kJ}$$

(Note: The positive sign indicates work is done on the air.)

To convert to power (work/time),

$$\text{kW} = \frac{2180 \text{ kJ}}{1 \text{ hr}} \left| \frac{1 \text{ kW}}{3600 \text{ s}} \right| = \boxed{0.61 \text{ kW}}$$

22.27

(a) Steady state process assumed.

$$\Delta E = -\Delta[(\hat{H} + \hat{K}E + \hat{P}E)m] + Q + W$$

1. Ignore $\hat{P}E$; $\Delta \hat{P}E = 0$

2. $\Delta \hat{K}E$ is small so $\Delta \hat{K}E = 0$

(continued)

Solutions Chapter 22

3. No reaction
 4. $W = 0$
 5. $(E_2 - E_1) = 0$, steady state

$$\Delta H = Q$$

(b) $\Delta E = -[(\hat{H} + \widehat{KE} + \widehat{PE})m] + Q + W$

1. Ignore $\widehat{PE}$; $\Delta \widehat{PE} = 0$
 2. No reaction
 3. $(E_2 - E_1) = 0$; steady state
 4. $Q = 0$ - assumed
 5. $W = 0$
 6. $\Delta \widehat{KE} = 0$

$$\Delta H = 0$$

22.28

System: gas

$$E_2 - E_1 = -\Delta[(\hat{H} + \widehat{KE} + \widehat{PE})m] + Q + W$$

a. no reaction

$$-\Delta[(\hat{H} + \widehat{KE} + \widehat{PE})m] = 0, \text{ no flow}$$

 ΔKE and ΔPE of gas = 0

$$U_2 - U_1 = Q + W$$

Solutions Chapter 22

b. Here $W = 0$

$$U_2 - U_1 = Q$$

c. Here $Q = 0$,

$$U_2 - U_1 = W$$

d.

$$U_2 - U_1 = Q + W$$

e. Here, the system is the gas $Q = 0$, $W = 0$

$$U_2 - U_1 = 0$$

22.29

Basis: 1 hour

Input conditions:

$$\left. \begin{array}{l} 500^\circ\text{F} \\ 250 \text{ psi} \end{array} \right\} h_1 = 1264.7 \text{ Btu/lb}$$

Exit conditions:

$$\left. \begin{array}{l} 14.7 \text{ psi} \\ 15\% \text{ liquid} \end{array} \right\} \begin{array}{l} h_{sv} = 1150.4 \text{ Btu/lb} \\ h_{sl} = 180.07 \text{ Btu/lb} \end{array}$$

$$\dot{H}_2 = 0.15(180.07) + 0.85(1150.4)$$

(continued)

Solutions Chapter 22

$$= 1004 \text{ Btu/lb}$$

The simplified energy balance is:

$$m\Delta\hat{H} = Q + W$$

$$\Delta\hat{H} = 1004 - 1265 = -261 \text{ Btu/lb}$$

$$m\Delta\hat{H} = -261,000 \text{ Btu}$$

$$W = -\frac{86.5 \text{ hp} \left| \frac{1 \text{ hr}}{2.93 \times 10^{-2} (\text{hp})(\text{hr})} \right| \frac{1 \text{ Btu}}{1}}{1} = -2.20 \times 10^5 \text{ Btu}$$

$$\text{Thus, } Q = m\Delta\hat{H} - W = -2.61 \times 10^5 + 2.2 \times 10^5 = -4.1 \times 10^4 \text{ Btu}$$

hence, not adiabatic.

22.30

Basis: 1 lb air

The energy balance is in the steady state. The system is the valve.

$$\Delta[(\hat{H} + \hat{KE} + \hat{PE})m] = Q + W$$

$$\text{if } \Delta\hat{KE} \cong 0 \quad W = 0$$

$$\Delta\hat{PE} = 0 \quad Q = 0$$

Hence $\Delta H = 0$

$$\Delta H = \int C_p dT = 0$$

Solutions Chapter 22

$$(a) \quad \Delta T = 0 \quad \text{or} \quad T_2 = 250 \text{ K}$$

Since $\Delta H = 0$ (the kinetic energy term was negligible), the steady-state constraint requires that the mass flow rate be constant:

$$\dot{m} = \rho v S = \text{Constant}$$

where: ρ = density

v = velocity of the gas

S = cross-sectional area of pipe

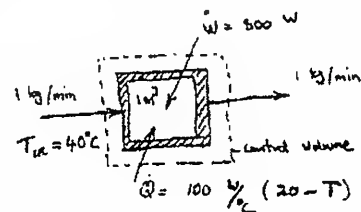
Since the diameter of the pipe does not change and density is a function of temperature and pressure, the gas velocity is also a function temperature and pressure.

$$v_{\text{STP}} = \frac{100 \text{ lb Air}}{1 \text{ hr}} \left| \frac{1 \text{ lb mol}}{29 \text{ lb Air}} \right| \left| \frac{359 \text{ ft}^3}{1 \text{ lb mol}} \right| \left| \frac{1 \text{ hr}}{3600 \text{ s}} \right| \left| \frac{1}{\pi(1.5/12 \text{ ft})^2} \right| = 7.0 \text{ ft/s}$$

Therefore, the velocity downstream of the valve is:

$$v_{\text{Outlet}} = \frac{7.0 \text{ ft}}{\text{s}} \left| \frac{250 \text{ K}}{273 \text{ K}} \right| \left| \frac{1 \text{ atm}}{2 \text{ atm}} \right| = 3.2 \text{ ft/s}$$

22.31



Steady-state process. Basis: 1 second

(continued)

$$\dot{m}(\hat{H}_{\text{out}} - \hat{H}_{\text{in}}) = \dot{Q} + \dot{W}$$

To get $\hat{H}_{\text{in}}$ use the steam tables or a C_p equation. Using constant C_p is not the most accurate method, but for liquids for small temperature changes, it is a good approximation.

$$(\dot{m})(C_p)(T_{\text{out}} - T_{\text{in}}) = \dot{Q} + \dot{W}$$

Because the tank is well-mixed, the outlet water temperature is the same as the temperature inside the tank T .

$$T = T_{\text{out}}$$

$$\dot{m}(C_p)(T - T_{\text{in}}) = 100(20 - T) + 300$$

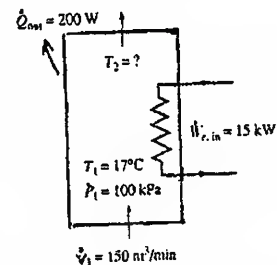
$$\dot{m} = \frac{1 \text{ kg}}{\text{min}} \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = \frac{1}{60} \frac{\text{kg}}{\text{s}}$$

$$C_p = 4180 \text{ J/(kg)(K)}$$

$$\frac{4180}{60}(T - 40) = 100(20 - T) + 300$$

$$T = 30.0^\circ\text{C}$$

22.32



Assumptions

1. This is a steady-flow process since there is no change with time at any point, hence $\Delta E = 0$.
2. Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point.
3. The kinetic and potential energy changes are negligible $\Delta KE \approx \Delta PE \approx 0$.
4. Constant specific heats at room temperature can be used for air.

The simplified energy balance is

$$\dot{Q} + \dot{W} = \Delta \hat{H} = m(\hat{H}_{\text{out}} - \hat{H}_{\text{in}})$$

$$\dot{Q} = -200 \text{ W}$$

$$\dot{W} = 15 \text{ kW}$$

Assume that with little error

(continued)

Solutions Chapter 22

$$\Delta H = C_p \Delta T \quad \text{with } C_p = 1.00 \text{ kJ/(kg)(}^\circ\text{C)}$$

Otherwise you will need tables or a data base for the properties of air.

The ideal gas law gives the specific volume of air at the inlet of the duct

$$\hat{V}_1 = \frac{RT_m}{p_{in}} = \frac{[(0.287 \text{ kPa})(\text{m}^3)/(\text{kg})(\text{K})](290 \text{ K})}{100 \text{ kPa}} = 0.832 \text{ m}^3/\text{kg}$$

The mass flow rate of the air through the duct is determined from

$$\dot{m} = \frac{\dot{V}_1}{\hat{V}_1} = \frac{150 \text{ m}^3/\text{min} \left(\frac{1 \text{ min}}{60 \text{ s}} \right)}{0.832 \text{ m}^3/\text{kg}} = 3.0 \text{ kg/s}$$

Substituting the known quantities, the exit temperature of the air is determined to be

$$(15 \text{ kJ/s}) - (0.2 \text{ kJ/s}) = (3 \text{ kg/s})[1.00 \text{ kJ/(kg)(}^\circ\text{C)}](T_{out} - 17)^\circ\text{C} \quad T_{out} = \boxed{21.9^\circ\text{C}}$$

22.33

The procedure is correct only for an open, steady state system.

(a) If the evaporation occurs from an open, unsteady-state system of fixed volume:

$$\Delta U = Q + W - \Delta H \quad W = 0$$

$$\Delta U = Q - \Delta H$$

Data:

$$\hat{U}_{liquid} = 419.5 \text{ kJ/kg} \quad \hat{U}_{vapor} = 2506.0 \text{ kJ/kg}$$

$$\hat{H}_{liquid} = 419.5 \text{ kJ/kg} \quad \hat{H}_{vapor} = 2675.6 \text{ kJ/kg}$$

Solutions Chapter 22

Assume only 1 kg of water is in the system at $t = \text{initial}$. At $t = \text{final}$, 0 kg of water are in the system.

$$U_{final} = 0$$

$$U_{initial} = (1 \text{ kg})(419.5 \text{ kJ/kg}) = 419.5 \text{ kJ}$$

$$H_{out} = (1 \text{ kg})(2675.6 \text{ kJ/kg}) = 2675.6 \text{ kJ}$$

$$H_{in} = 0$$

$$-419.5 = Q - (2675.6 - 0)$$

$$Q = 2256.1 \text{ kJ}$$

(b) If the evaporation occurs in a steady-state open system, m_{in} is in kg and $m_{in} - 1 = m_{out}$. The process is isothermal.

$$W = 0$$

$$\Delta U = 0$$

$$Q = \Delta H = \left[(m_{in} - 1) \hat{H}_{liquid}^{OUT} + (1) \hat{H}_{vapor}^{IN} \right] - m_{in} \hat{H}_{in}$$

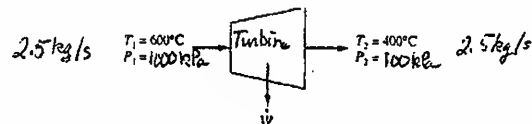
$$\hat{H}_{in} = \hat{H}_{liquid}$$

$$Q = (1)(2675.6 - 419.5) = 2256.1 \text{ kJ}$$

The answer in the solution is ok, but note that the equation $\Delta U = Q - p\Delta V$ refers to a closed system, not an open one, in which the vessel expands against the atmosphere. This viewpoint is ok, but an unlikely procedure.

Solutions Chapter 22

22.34



Open, unsteady state system – the adiabatic turbine

$$\Delta \dot{U} = 0 \quad \dot{Q} = 0 \quad \Delta \dot{P}E = 0$$

$$\dot{W} = \Delta \dot{H} + \Delta \dot{KE}$$

Data from interpolating in the SI steam tables

At 600°C and 100 kPa

At 400°C and 100 kPa

3697.9	$\hat{H}(\text{kJ/kg})$	3278.2
0.4011	$\hat{V}(\text{m}^3/\text{kg})$	3.103

The velocities at the inlet and outlet to the turbine are calculated from the volumetric flow rate = $\dot{m}\hat{V} = \frac{\pi d^2}{4} v$ where d is the pipe diameter. Therefore,

$$v_1 = \frac{4\dot{m}_1\hat{V}_1}{\pi d_{in}^2} = \frac{(4)\left(2.5 \frac{\text{kg}}{\text{s}}\right)\left(0.4011 \frac{\text{m}^3}{\text{kg}}\right)}{(3.14159)(0.1 \text{ m})^2} = 127.7 \frac{\text{m}}{\text{s}},$$

$$\text{and } v_2 = \frac{4\dot{m}_2\hat{V}_2}{\pi d_{out}^2} = 158.0 \frac{\text{m}}{\text{s}}$$

Solutions Chapter 22

$$\Delta \dot{KE} = \left(\frac{1}{2}\right)(2.5)\left[158.0^2 - 127.7^2\right]\left(\frac{1}{100}\right) \text{ kJ/s} = 10.82 \text{ kJ/s}$$

$$\Delta \dot{H} = (2.5)(3278.2 - 3697.9) \text{ kJ/s} = -1049.25 \text{ kJ/s}$$

$$\dot{W} = -1049.25 + 10.82 = \boxed{1038.4 \text{ kJ/s}} \\ \boxed{(1038.4 \text{ kW})}$$

23.1

Any correct examples will be satisfactory for (2), (3), and (4). But for (1), liquid to solid, there are probably no examples. If any, they would be pathological cases.

23.2

Sensible heat refers to the enthalpy change when a compound goes from one temperature to another without a phase change. Latent heat is the enthalpy change that occurs during a phase transition. Generally latent heat is much greater than sensible heat.

23.3

Yes.

23.4

(1) Solid melting.

23.5

(a) 1; (b) 3; (c) 5; (d) 2; (e) 4

The boiling temperature is at 4 reading to the left scale (100°C)
The freezing temperature is at 1 reading to the left scale (0°C)

23.6

$$\Delta \hat{U}_{\text{fusion}} = \Delta \hat{H}_{\text{fusion}} - \Delta(p\hat{V})_{\text{fusion}}$$

$\Delta(p\hat{V}) = p(\hat{V}_{\text{liquid}} - \hat{V}_{\text{solid}}) \cong 0$ because there is essentially no change on melting for most substances, and whatever change there is, relative to $\Delta \hat{H}_{\text{fusion}}$, the $\Delta(p\hat{V})_{\text{fusion}}$ is very small.

23.7

Vapor pressure equation:

$$\log p = \frac{-6160}{T} + 8.10, (T \text{ in K})$$

Clausius-Clapeyron equation:

$$\frac{d(\log p)}{dT} = \frac{\Delta \hat{H}_v}{2.303 RT^2}$$

Differentiate the first equation:

$$\frac{d(\log p)}{dT} = \frac{d}{dT} \left[\frac{-6160}{T} + 8.10 \right] = \frac{+6160}{T^2}$$

Equate the two equations:

$$\frac{\Delta \hat{H}_v}{2.303 RT^2} = \frac{6160}{T^2}$$

$$\Delta \hat{H}_v = (6160)(2.303)(R)$$

$$= (6160)(2.303) \begin{Bmatrix} 1.987 \\ 1.987 \\ 8.314 \end{Bmatrix} = \begin{Bmatrix} 28,190 \text{ cal/g mol} \\ 28,190 \text{ Btu/lb mol} \\ 117,950 \text{ J/g mol} \end{Bmatrix}$$

23.8

Equate the derivative of the Antoine equation ($d \ln(p^*)/dT$) to the equivalent in the Clausius - Clapeyron equation

$$200^\circ\text{F} = 660^\circ\text{R} = 366.7 \text{ K}$$

$$\frac{dp^*}{dT} = \frac{\Delta \hat{H}_v}{T(\hat{V}_g - \hat{V}_l)}$$

$$\begin{array}{l} \text{ignore } \hat{V}_l \\ \text{insert } p\hat{V} = RT \\ RT \end{array}$$

$$\frac{dp^*}{dT} = \frac{\Delta \hat{H}_v}{T \left(\frac{RT}{p^*} \right)}$$

$$\frac{dp^*}{p^*} = d \ln p^* \quad \text{so that} \quad \frac{d \ln p^*}{dT} = \frac{\Delta \hat{H}_v}{RT^2}$$

$$\frac{d \log_{10} p^*}{dT} = \frac{\Delta \hat{H}_v}{2.3 RT^2} \quad T_K = T_{^{\circ}\text{C}} + 273$$

$$\text{Antoine eq:} \quad \log_{10} p^* = 7.9046 - \frac{2366.4}{T + 230}$$

Differentiate the Antoine equation:

$$\frac{d \log_{10} p^*}{dT} = 0 - \frac{2366.4}{(T_K - 43)^2} (-1) = \frac{\Delta \hat{H}_v}{2.3(1.987)T_K^2}$$

$$\Delta \hat{H}_v = \frac{(2.3)(8.314)(366.7)^2(2366.4)}{(366.7 - 43)^2} = \boxed{58,070 \frac{\text{J}}{\text{g mol}}}$$

$$\boxed{2.49 \times 10^4 \text{ Btu/lb mol}}$$

23.9

C_6H_6 MW = 78

Assume: $\Delta \hat{H}_v$ is constant, ideal gas

$$\frac{dp^*}{dT} = \frac{\Delta \hat{H}_v}{T(\hat{V}_g - \hat{V}_l)}$$

$$\hat{V}_g \gg \hat{V}_l$$

$$35^{\circ}\text{C} = 308 \text{ K}$$

$$p\hat{V} = RT \text{ for 1 mol (basis)}$$

$$\Delta \hat{H} = 841.5 - 423.8 = 417.7 \text{ J/g}$$

$$\frac{dp^*}{dT} = \frac{\Delta \hat{H}_v}{T \left(\frac{RT}{p^*} \right)} \quad \text{or} \quad \frac{dp^*}{p^*} = \frac{\Delta \hat{H}_v}{R} \frac{dT}{T^2}$$

Integrate between 308 K and 320 K

$$\int_{T_1=308}^{T_2=320} \frac{dT}{T^2} = -\left[\frac{1}{T} \right]_{T_1}^{T_2}$$

$$\ln \left(\frac{0.2111}{p_{35}^*} \right) = \frac{\Delta \hat{H}_v}{R} \left[\frac{1}{T_1} - \frac{1}{T_2} \right] = \frac{\Delta \hat{H}_v}{R} \left[\frac{1}{308} - \frac{1}{320} \right]$$

$$-1.5554 - \ln p_{35}^* = \frac{417.7 \text{ J}}{\text{g}} \left| \frac{78 \text{ g}}{1 \text{ g mol}} \right| \frac{1}{\left(\frac{8.314 \text{ J}}{(\text{g mol})(\text{K})} \right)} \left| \frac{0.1218 \times 10^{-3}}{\text{K}} \right| = 0.4771$$

$$p_{35}^* = \boxed{0.1310 \text{ atm}}$$

23.10

$$T_c = 540.2 \text{ K} \quad p_c = 27 \text{ atm}$$

$$\Delta H_v = T_b \frac{0.0331 \left(\frac{T_b}{T_c} \right) - 0.0327 + 0.0297 \log(p_c)}{1.07 - \left(\frac{T_b}{T_c} \right)} \frac{\text{kJ}}{(\text{g mol})(\text{K})}$$

$$\Delta H_v = 31.679 \frac{\text{kJ}}{\text{g mol}}$$

The percent error is negligible in view of the precision of the data.

23.11

From Appendix D1 the normal boiling point of benzene is at 353.26 K, $T_c = 562.6 \text{ K}$, and $p_c = 48.6 \text{ atm}$.

Riedel's equation is

$$\Delta H_v = 1.093 RT_c \left[\frac{T_b}{T_c} \times \frac{(\ln p_c - 1)}{0.930 - (T_b/T_c)} \right]$$

$$= \frac{1.093}{\left(\frac{8.314 \text{ J}}{(\text{g mol})(\text{K})} \right)} \left| \frac{562.6 \text{ K}}{562.6 \text{ K}} \right| \left| \frac{353.26 \text{ K}}{0.930 - (353.26 \text{ K} / 562.6 \text{ K})} \right| \left| \frac{[\ln(48.6) - 1]}{562.6 \text{ K}} \right|$$

(continued)

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$$\Delta H_v = 30641 \text{ J/g mol or } \boxed{30.64 \text{ kJ/g mol}}$$

The experimental value from the Appendix is 30.76 kJ/g mol.

23.12

$$\Delta H_v = 312.13 \text{ kJ/kg at } T_i = 152.4^\circ\text{C} ; T_c = 360^\circ\text{C}$$

Molecular weight = 120

$$\text{Watson Equation: } \Delta H_v \text{ at } 100^\circ\text{C} = 312.13 \left[\frac{360 - 100}{360 - 152.4} \right]^{0.38} = 340.3 \text{ kJ/kg}$$

23.13

The following vapor pressure data are needed

	$T(^{\circ}\text{C})$	$p(\text{mm Hg})$
Ice	-4	3.280
	-2	3.880
Water	+2	5.294
	+4	6.101

In the Clausius-Clapeyron equation the heat of vaporization is a function of temperature; however, if it is assumed to be independent of temperature the equation can be integrated to give

$$\ln \frac{p_{\text{vap}}(T_2)}{p_{\text{vap}}(T_1)} = -\frac{\Delta H_{\text{vap}}}{R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)$$

a result that is also valid over small temperature ranges when ΔH_{vap} is temperature dependent. The integrated equation has been found to be fairly accurate for correlating the temperature dependence of the vapor pressure of liquids over limited temperature ranges.

(a) For the ice sublimating

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$$\frac{\Delta H_{\text{sub}}}{R} = -\frac{\ln [p_{\text{sub}}(T_2)/p_{\text{sub}}(T_1)]}{\frac{1}{T_2} - \frac{1}{T_1}} = -\frac{\ln \left(\frac{3.880}{3.280} \right)}{\frac{1}{271.15 \text{ K}} - \frac{1}{269.15 \text{ K}}} = 6130 \text{ K}$$

so that

$$\Delta H_{\text{sub}} = (6130 \text{ K}) \left(8.314 \frac{\text{J}}{(\text{g mol})(\text{K})} \right) = \boxed{50.97 \frac{\text{kJ}}{\text{g mol}}}$$

(b) For the water vaporizing

$$\frac{\Delta H_{\text{vap}}}{R} = -\frac{\ln [p_{\text{vap}}(T_2)/p_{\text{vap}}(T_1)]}{\frac{1}{T_2} - \frac{1}{T_1}} = -\frac{\ln \left(\frac{6.101}{5.294} \right)}{\frac{1}{277.15 \text{ K}} - \frac{1}{275.15 \text{ K}}} = 5410 \text{ K}$$

$$\Delta H_{\text{vap}} = (5410 \text{ K}) \left(8.314 \frac{\text{J}}{(\text{g mol})(\text{K})} \right) = \boxed{44.98 \frac{\text{kJ}}{\text{g mol}}}$$

(c) For fusion of ice

Since

$$\Delta H_{\text{sub}} = H(\text{vapor}) - H(\text{solid})$$

and

$$\Delta H_{\text{vap}} = H(\text{vapor}) - H(\text{liquid})$$

it then follows that

$$\Delta H_{\text{fus}} = H(\text{liquid}) - H(\text{solid}) = \Delta H_{\text{sub}} - \Delta H_{\text{vap}} = 50.97 - 44.98 = \boxed{5.99 \frac{\text{kJ}}{\text{g mol}}}$$

(d) At the triple point temperature T_T , the sublimation pressure of the solid and the vapor pressure of the liquid are equal; we denote this triple point pressure as p_T . Use the integrated equation for both the solid and liquid phases to get

$$\frac{\Delta H_{\text{sub}}}{R} = 6130 = -\frac{\ln\left(\frac{p_r}{p_{\text{sub}}(T)}\right)}{\frac{1}{T_r} - \frac{1}{T}} = -\frac{\ln\left(\frac{p_r}{3.880}\right)}{\frac{1}{T_r} - \frac{1}{271.15}}$$

and

$$\frac{\Delta H_{\text{vap}}}{R} = 5410 = -\frac{\ln\left(\frac{p_r}{p_{\text{vap}}(T)}\right)}{\frac{1}{T_r} - \frac{1}{T}} = -\frac{\ln\left(\frac{p_r}{5.294}\right)}{\frac{1}{T_r} - \frac{1}{275.15}}$$

The solution to this pair of equations is $T_r = 273.3$ K, and $p_r = 4.63$ mm Hg. The reported triple point is 273.16 K and 4.579 mm Hg, so the estimate is quite good.

23.14

Basis: 1.0 g of $n\text{-C}_4\text{H}_{10}$ Given: $(\text{sp.gr})_{\text{liquid}} = 0.564 \text{ g/cm}^3$

$$\hat{V}_{\text{liquid}} = \frac{1}{(0.564)(1)} = 1.77 \frac{\text{cm}^3}{\text{g}}$$

 $(\text{sp.gr})_{\text{vapor}} = 6.50$

$$\hat{V}_{\text{vapor}} = \frac{1}{(6.50)(1.293)} = 119 \frac{\text{cm}^3}{\text{g}}$$

 $\Delta \hat{H}_{\text{vap}} = 356.5 \text{ J/g}$

$$\log_{10}(p) = 1.767 - \frac{1,337}{T} + 1.75 \log_{10} T - 0.004T$$

Apply the Clapeyron equation for the vapor liquid transition at 30°C

$$\frac{dp}{dT} = \frac{\Delta \hat{H}_{\text{vap}}}{T \Delta \hat{V}} = \frac{\Delta \hat{H}_{\text{vap}}}{T(\hat{V}_{\text{vapor}} - \hat{V}_{\text{liquid}})}$$

If the data is consist it must satisfy the Clapeyron equation

Thus,

$$\begin{aligned} \frac{dp}{dT} &= \frac{d \ln p}{dT} (p) = \frac{d(2.303 \log p)}{dT} (p) \\ &= (2.303) \left[\frac{1,337}{T^2} + (1.75)(2.303) \frac{1}{T} - 0.004 \right] (p) \end{aligned}$$

At 30°C

$$\begin{aligned} \log_{10}(p) &= 1.767 - \frac{1,337}{303} + 1.75 \log_{10}(303) - 0.004(303) \\ &= 1.767 - 4.42 + 4.35 - 1.21 = 0.487 \end{aligned}$$

Solve for $p = 3.07$ atm

$$\frac{dp}{dT} = (0.0528)(3.07) = 0.162 \frac{\text{atm}}{\text{K}}$$

In this case $\frac{\Delta \hat{H}_{\text{vap}}}{T \Delta \hat{V}} = \frac{356.5}{(303) \Delta \hat{V}}$

$$\begin{aligned} &= \frac{\left(356.5 \frac{\text{J}}{\text{g}}\right) \left[4.13 \times 10^{-2} (\text{L})(\text{atm})\right]}{(303 \text{ K})(0.119 - 0.00177) \frac{\text{L}}{\text{g}}} \\ &= \frac{(356.5) \left[4.13 \times 10^{-2} (\text{atm})\right]}{(303)(0.117)} \frac{\text{atm}}{\text{K}} = 0.0995 \frac{\text{atm}}{\text{K}} \end{aligned}$$

Conclusion: The given data are not consistent

It shows $\frac{dp}{dT} > \frac{\Delta \hat{H}_{\text{vap}}}{T \Delta \hat{V}}$

23.15

Due to the density difference, the water had settled out at the base of the vessel below the heating oils and had remained cold while the oil was heated up to a temperature in excess of 100°C. When the agitator was started the water was brought into contact with the oil and immediately vaporized under the surface of the oil to form an enormous volume of steam.

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Even if the operator had not started the agitator at this time it is highly likely that the result would have been the same. Some of the water would, in time have been heated to boiling point by conduction and the violent mixing resulting from the boiling process would have achieved the same result.

23.16

Below log is $\log_{10}$. The critical temperature = 408.1 K

$$C_p = A + B \log T_i$$

Basis: 1 g mol

$$B = \frac{C_{p_i} - C_{p_f}}{\log T_{f_i} - \log T_{f_e}} \quad ; \quad A = C_{p_i} - B \log T_{f_i}$$

$$C_{p_i} = 97.3 \quad T_{f_i} = 300 / 408.1 = 0.735 \quad \log T_{f_i} = -0.134$$

$$C_{p_f} = 149.0 \quad T_{f_e} = 500 / 408.1 = 1.225 \quad \log T_{f_e} = 0.088$$

$$A = 128.5 \quad B = 232.6$$

$$\text{at } 1000 \text{ K: } T_{1000} = 1000 / 408.1 = 2.45 \quad \log T_{1000} = 0.389$$

$$C_p = 128.5 + 232.6(0.389) = \boxed{219.0 \text{ J/(g mol)(K)}}$$

$$(100) \frac{227.6 - 219.0}{227.6} = \boxed{3.8\%}$$

23.17

Solution via Polymath:

$$C_p = 34.5864 + 0.0356677T - 7.9955 \times 10^{-6}T^2$$

$$C_p = 34.8264 + 0.0326495T - 1.45 \times 10^{-6}T^2 - 3.6363 \times 10^{-9}T^3$$

The heat capacity equation for NH_3 gas from Appendix E is

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23.18

A second order fit is only good above 300°C. As a guide for an answer:

$$C_p = 8.3810 + 7.9891 \times 10^{-3}T - 1.5055 \times 10^{-6}T^2$$

and

$$C_p = 8.4017 + 7.0601 \times 10^{-3}T + 1.0567 \times 10^{-6}T^2 - 1.5981 \times 10^{-9}T^3$$

with average deviations of 0.55% and 0.36% and maximum deviations of 1.48% and 0.91%.

23.19

Equation is

$$C_p = 36.7 + 0.0403T - 0.0000221T^2$$

23.20

To convert J/(g mol) (°C) to Btu/(lb mol) (°F)

$$\frac{\text{J}}{(\text{g mol}) (^\circ\text{C})} \left| \frac{1 \text{ cal}}{4.184 \text{ J}} \right| \left| \frac{1 \text{ Btu}}{252 \text{ cal}} \right| \left| \frac{454 \text{ g}}{1 \text{ lb}} \right| \left| \frac{(1 \Delta ^\circ\text{C})}{(1.8 \Delta ^\circ\text{F})} \right|$$

Hence the right hand side of the heat capacity equation has to be multiplied by 1/4.184.

To convert the temperatures in °C to T in °F, substitute

$$T_{^\circ\text{C}} = \frac{T_{^\circ\text{F}} - 32}{1.8}$$

$$C_p \left(\frac{\text{Btu}}{(\text{lb mol})(^\circ\text{F})} \right) = 17.20 + 4.80 \times 10^{-2} \left(\frac{T_{^\circ\text{F}} - 32}{1.8} \right) - 3.054 \times 10^{-5} \left(\frac{T_{^\circ\text{F}} - 32}{1.8} \right)^2 + 8.308 \times 10^{-9} \left(\frac{T_{^\circ\text{F}} - 32}{1.8} \right)^3$$

23.21

a. $T_K = T_{°C} + 273.2$ so that

$$C_p = 6.39 + 1.76 \times 10^{-3} (T_{°C} + 273.2) - 0.26 \times 10^{-6} (T_{°C} + 273.2)^2$$

$$C_p = 6.852 + 1.62 \times 10^{-3} T_{°C} - 0.26 \times 10^{-6} T_{°C}^2$$

b. $T_{°C} = (T_{°F} - 32)/1.8$ Multiply the whole equation above by 1/29 to get Btu/(lb)(°F) and insert $T_{°C} = \frac{T_{°F} - 32}{1.8}$

$$C_p = \frac{6.892 \text{ cal}}{(\text{g mol})(°C)} \left| \frac{454 \text{ g mol}}{1 \text{ lb mol}} \right| \left| \frac{1 \text{ Btu}}{252 \text{ cal}} \right| \left| \frac{1 \text{ lb mol}}{29 \text{ lb}} \right| \left| \frac{1 \Delta °C}{1.8 \Delta °F} \right|$$

$$+ \frac{1.62 \times 10^{-3} \text{ cal}}{(\text{g mol})(\Delta °C)(°C)} \left| \frac{454 \text{ g mol}}{1 \text{ lb mol}} \right| \left| \frac{1 \text{ Btu}}{252 \text{ cal}} \right| \left| \frac{1 \Delta °C}{1.8 \Delta °F} \right| \left| \frac{(T_{°F} - 32)}{1.8} \right| \left| \frac{°C}{1.8} \right| \left| \frac{1 \text{ lb mol}}{29 \text{ lb}} \right|$$

$$- \frac{0.26 \times 10^{-6} \text{ cal}}{(\text{g mol})(\Delta °C)^2(°C)^2} \left| \frac{454 \text{ g mol}}{1 \text{ lb mol}} \right| \left| \frac{1 \text{ Btu}}{252 \text{ cal}} \right| \left| \frac{1 \Delta °C}{1.8 \Delta °F} \right| \left| \frac{(T_{°F} - 32)}{1.8} \right|^2 \left| \frac{°C^2}{1.8} \right| \left| \frac{1 \text{ lb mol}}{29 \text{ lb}} \right|$$

$$C_p = 0.263 + 3.118 \times 10^{-5} T_{°F} - 2.765 \times 10^{-9} T_{°F}^2$$

23.22

Basis: 1 lb

$$\Delta H = \int_{H_1}^{H_2} dH = H_2 - H_1 = 1510 \text{ Btu/lb} \quad T_1 = 1000^\circ\text{F}$$

$$= \int_{T_0}^{T_1} C_p dT = 1.2(1000 - T_0) + \frac{0.0050}{2}(1000^2 - T_0^2)$$

$$- \frac{2.1 \times 10^{-6}}{3}(1000^3 - T_0^3)$$

$$= 1200 - 1.2T_0 + 0.0025 \times 10^6 + 0.7 \times 10^{-6} \times 10^9$$

23.23

No. The enthalpy and internal energy must be changes, and each has a reference point. The calculation should be

$$\Delta \hat{U} = \Delta \hat{H} - \Delta(p\hat{V}) = (16,660 - \Delta \hat{H}_{\text{ref}}) - (p_{600 \text{ kPa}} \hat{V}_{600 \text{ kPa}, 283 \text{ K}} - p_{\text{ref}} \hat{V}_{\text{ref}})$$

If the reference for CO₂ is saturated liquid at 233K, $\Delta H_{\text{ref}} = 0$ kJ/g mol. If the reference is at the triple point of CO₂, the enthalpy calculated is in error.

23.24

Differentiate the enthalpy equation

$$\frac{d(H)}{dT} = C_p(T) = 92.38 + 3.754 \times 10^{-2} T - \frac{2.186 \times 10^6}{T^2}$$

23.25

Not valid because introduction of $T = 298$ into the equation does not yield $H(298) - H(298) = 0$.

23.26

Basis: 1 kg mol O₂

O ₂ (ℓ)	ΔH_{vap}	O ₂ (g)	_____	O ₂ (g)
satd.	90.19K	satd.	1.5 atm	
			27°C	

$$\Delta \hat{H}_{\text{vap}} = 6.820 \text{ kJ/g mol}$$

$$\Delta \hat{H} = 6.820 \text{ kJ} + [7.104(80.6 - (-297.7))] + \frac{0.0785 \times 10^{-2}}{2}$$

$$(90.19 \text{ K} - 273.15 \text{ K}) + 0.00553 \times 10^{-5} (90.19 \text{ K} - 273.15 \text{ K})^2 \text{ Btu}$$

$$\times \left[\frac{1055 \text{ J}}{1 \text{ Btu}} \left| \frac{1 \text{ lb}}{0.454 \text{ g}} \right| \right] = \boxed{12.99 \text{ kJ}}$$

23.27

$$\Delta H = 2 \int_{25+273}^{250+273} (27.32 + 0.6226 \times 10^{-2} T - 0.0950 \times 10^{-5} T^2) dT$$

$$\boxed{\Delta H = 11,980 \text{ J}} \quad (\text{The CD gives } 11,784 \text{ J})$$

23.28

Integrate the heat capacity equation, or interpolate in Table D6 in the Appendix. From the latter (easier)

$$\Delta H = -5 \times 10^5 (29,154 - 9,665) = \boxed{-97,445 \text{ kJ}}$$

23.29

Integrate the heat capacity equation, use Table D5 in the Appendix, or use CD

From the CD $\Delta H = 5789 \text{ J/g mol}$

23.30

Integrate the heat capacity equation, use Table D3 in the Appendix, or use CD

From the CD $\Delta H = 2580 \text{ J/g mol}$

23.31

The volume of the wire is $\left(\frac{\pi D^2}{4} \right) 5.5 = \pi \frac{(0.25)^2}{4} (5.5) = 0.27 \text{ cm}^3$. The density of Al is 19.35 g/cm^3 , so $19.35(0.27) = 5.22 \text{ g}$ or 0.194 g mol Al . From Perry, $C_p = 20.0 + 0.0135T$ (T in K, C_p in $\text{J/(g mol)}(^{\circ}\text{C})$) and $\Delta H_{\text{fusion}} = 10,670 \text{ J/g mol}$ at 660°C .

$$\Delta H = 0.194 \left[\int_{25+273}^{660+273} (20.0 + 0.0135T) dT + 10,670 \right] = 5560 \text{ J}$$

$$5560(2.773 \times 10^{-7}) = 1.54 \times 10^{-3} \text{ kWh}$$

23.32

Basis: 1 g mol

Integrate the respective C_p equations in the appendix or use the CD. Multiply the resulting J/g mol by 0.80 and 0.20 for CH_4 and C_2H_6 , respectively.

$$\text{Result using the CD: } \boxed{2.88 \times 10^7 \text{ J/kg mol}}$$

23.33

Basis: 100 mol gas

Comp.	mol
CO	68
H ₂	30
CO ₂	<u>2</u>
	100

$\Delta \hat{H} \text{ (J/g mol) relative to } 0^{\circ}\text{C and } 1 \text{ atm}$

		CO	H ₂	CO ₂
25°C =	298 K	728	718	912
	1500 K	39,576	36,994	62,676
1400°C =	1673 K	45,723	42,724	72,896
	1750 K	48,459	45,275	77,445

$$\frac{1000 \text{ m}^3}{1673 \text{ K}} \left| \frac{273 \text{ K}}{22.4 \text{ m}^3} \right| \frac{1 \text{ kg mol}}{22.4 \text{ m}^3} = 7.28 \text{ kg mol}$$

Calculation of ΔH :

	kg mol	$\Delta \hat{H}$ (kJ/kg mol)	ΔH (kJ)
CO	7.28 (.68)	-44,995	-222,743
H ₂	7.28 (.30)	-42,010	-91,750
CO ₂	7.28 (.02)	-71,984	-10,481
			-325,000

23.34

Basis: 1 g mol SO₂ (g) at 538°C

$$\Delta H = \int_{538}^{-5} (33.97 + 2.856 \times 10^{-2} T_{\text{°C}} - 8.79 \times 10^{-6} T_{\text{°C}}^2) dT$$

$$+ (-24,940) + \int_{-5}^{-75.5} (1.28) dT + (-7,401) + \int_{-75.5}^{-101} (0.958) dT$$

$$= \left[33.97(-5 - 538) + \frac{2.856 \times 10^{-2}}{2} ((-5)^2 - (538)^2) \right.$$

$$\left. - \frac{8.79 \times 10^{-6}}{3} [(-5)^3 - (538)^3] \right] - 24,940 + (1.28)[(-75.5) - (-5)]$$

$$- 7,401 + (0.958)[(-101) - (-75.5)] = -22,133 - 24,940 - 90 - 7,401 - 24 = -54,590 \text{ J}$$

23.35

K	°C	°F	
423	150.0	302	vapor
			↓
353.3	80.1	176	satd vapor → satd liquid
			↓
278.7	5.5	42	Satd liquid → satd solid
			↓

Basis: 1 g mol

From Table D.1 in the Appendix.

Benzene properties:

Mol. wt.	78.11	Boiling point	353.26 K
Melting point	278.69 K	$\Delta H_{\text{vaporization}}$	30.76 kJ/g mol
ΔH fusion	984 kJ/g mol		

K	°C
423	150
353.26	80.11
278.69	5.54
253	-20

Heat Capacity Equation Coefficients:

	a	b	c	d	T
Benzene(g)	74.06	32.95×10^{-2}	-25.20×10^{-5}	77.57×10^{-9}	°C
Benzene(l)	62.55	23.9×10^{-2}	-	-	K

The C_p equation is in °C hence the limits on integration should be in °C. $\Delta H_1 =$

$$\int_{423}^{353} (74.06 + 32.95 \times 10^{-2} T - 25.20 \times 10^{-5} T^2 + 77.57 \times 10^{-9} T^3) dT = -11,790 \text{ J/g mol}$$

Condensation

$$\Delta H_2 = -3.076 \times 10^4 \text{ J/g mol}$$

Liquid

$$\Delta H_3 = \int_{353.26}^{278.69} (62.55 + 23.4 \times 10^{-2} T) dT = -10,180 \text{ J/g mol}$$

Fusion

$$\Delta H_4 = -9.84 \times 10^3 \text{ J/g mol}$$

(continued)

SolidFrom Perry, 5th edition:

	$C_p \text{ (cal)/(g)(}^\circ\text{C)}$	$C_p \text{ (J/(g mol)(}^\circ\text{C))}$
0°C	0.375	12.3
-50°C	0.299	97.7

If a linear relationship exists between C_p and T ,

$$C_{p,av} = 119 \text{ J/(g mol)} (^\circ\text{C}) \quad -11,790$$

$$\Delta H_s = \int_{3.5}^{-20.0} (119) dT = -3034 \text{ J/g mol} \quad -30,760$$

$$-10,180$$

$$\text{Overall, } \Delta H = \sum_{i=1}^4 \Delta H_i = -65,604 \text{ J/g mol} \quad -9,840$$

$$\frac{-3,034}{-65,604}$$

$$\frac{-65,604 \text{ J/g mol}}{78.11 \text{ kg}} = -8.40 \times 10^5 \text{ J/kg}$$

23.36

$$T_1 = 573 \text{ K} \quad T_2 = 423 \text{ K}$$

$$\Delta H = m \int_{T_1}^{T_2} C_p dT$$

$$\int_{T_1}^{T_2} C_p dT = 7.24 \Delta T - \frac{1.76}{2} \times 10^{-3} (T_2^2 - T_1^2) + \frac{3.07 \times 10^{-6}}{3} (T_2^3 - T_1^3)$$

$$+ \frac{1 \times 10^{-9}}{4} (T_2^4 - T_1^4) = -1088.6 \frac{\text{kJ}}{\text{kg mol}}$$

$$\Delta H = (100 \text{ kg}) (-1088.6 \frac{\text{kJ}}{\text{kg mol}}) (\frac{1 \text{ kg mol}}{36.5 \text{ kg}}) (\frac{4.18 \text{ kJ}}{\text{kJ}}) = -12,467 \text{ kJ}$$

$$\Delta H = \Delta U + \Delta(pV) = \Delta U + p(V_2 - V_1)$$

Assuming HCl is an ideal gas

$$V = \frac{nRT}{p} \text{ so } p\Delta V = nR\Delta T$$

$$\text{Then } \Delta U = \Delta H - nR\Delta T$$

$$= -12,467 \text{ kJ} - (100 \text{ kg}) (\frac{\text{kJ}}{36.5 \text{ kg}}) (\frac{8.314 \text{ kJ}}{\text{kg mol K}}) (-150 \text{ K}) = \boxed{-9050 \text{ kJ}}$$

23.37

Basis: 1 lb mol

6.00 lb mol gaseous H₂O, 4.00 lb mol CO₂

Heated from 60°F (15.6°C) to 600°F (315.6°C)

From appendix E for H₂O:

$$\Delta \hat{H} = \int_{15.6}^{315.6} (33.46 + 0.6880 \times 10^{-2} T + 0.7604 \times 10^{-5} T^2 - 3.593 \times 10^{-9} T^3) dT$$

$$= 33.46 (315.6 - 15.6) + \frac{0.6880 \times 10^{-2}}{2} (315.6^2 - 15.6^2) \\ + \frac{0.7604 \times 10^{-5}}{3} (315.6^3 - 15.6^3) - \frac{3.593 \times 10^{-9}}{4} (315.6^4 - 15.6^4)$$

$$\Delta \hat{H} = 1.045 \times 10^4 \text{ J/g mol}$$

$$\frac{1.045 \times 10^4 \text{ J}}{\text{g mol}} \left| \frac{454 \text{ g mol}}{\text{lb mol}} \right| \frac{9.484 \times 10^{-4} \text{ Btu}}{\text{J}} = 4.499 \times 10^3 \text{ Btu/lb mol}$$

For CO₂ in Btu/(lb mol)(°F):

$$\Delta \hat{H} = \int_{60}^{600} (8.448 + 0.5757 \times 10^{-2} T - 0.2159 \times 10^{-5} T^2 + 0.3059 \times 10^{-9} T^3) dT$$

(continued)

$$= 8.448 (600 - 60) + \frac{0.5757 \times 10^{-2}}{2} (600^2 - 60^2) - \frac{0.2159 \times 10^{-5}}{3} (600^3 - 60^3) \\ + \frac{0.3059 \times 10^{-9}}{4} (600^4 - 60^4)$$

$$\Delta \hat{H} = 5.442 \times 10^3 \text{ Btu/lb mol}$$

$$\Delta H = (4.499 \times 10^3 \text{ Btu/lb mol}) (6.00 \text{ lb mol}) + (5.442 \times 10^3 \text{ Btu/lb mol}) (4.00 \text{ lb mol})$$

$$\Delta H = 4.88 \times 10^4 \text{ Btu}$$

23.38

Basis: liquid water at 32°F and 1 atm

$$a. \Delta H = 3(\Delta \hat{H}_{300^\circ\text{F}, 1 \text{ atm}} - \Delta \hat{H}_{32^\circ\text{F}, 1 \text{ atm}}) = 3(1192 - 0) = 3576 \text{ Btu}$$

b. Basis: liquid water at 40°F and 60 psia

$$\Delta \hat{H}_{32^\circ\text{F}, 60 \text{ psia}} = 0 \quad \Delta H = 3(1192 - 0) = 3576 \text{ Btu}$$

c. Basis: liquid water 40°F and 60 psia

$$\Delta H = (\Delta \hat{H}_{300^\circ\text{F}, 60 \text{ psia}} - \Delta \hat{H}_{40^\circ\text{F}, 60 \text{ psia}}) = (1181.4 - 8.05) \\ = 1173.4 \text{ Btu}$$

d. Basis: water-steam mixture of 60% quality

State		$\Delta \hat{H}$, Btu/lb
1	60% steam - 40% water at 300°F; sat'd steam	1179.7
2	80% steam - 20% water at 300°F; water	269.6

$$\Delta \hat{H} = \Delta \hat{H}_2 - \Delta \hat{H}_1$$

$$\Delta \hat{H}_2 = (0.80)(1179.7) + (0.20)(269.6) = 998 \text{ Btu/lb}$$

$$\Delta \hat{H}_1 = (0.60)(1179.7) + (0.40)(269.6) = 816 \text{ Btu/lb}$$

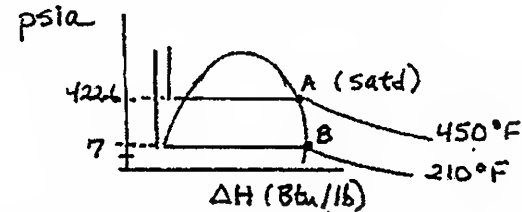
Enthalpy change needed = $\Delta \hat{H}$

$$\Delta \hat{H} = \Delta \hat{H}_2 - \Delta \hat{H}_1 = 182 \text{ Btu/lb}$$

c. Basis: steam at 500°F and 120 psia

$$\Delta \hat{H} = \Delta \hat{H}_2 - \Delta \hat{H}_1 = 312.5 - 1276.7 = -964.2 \text{ Btu/lb}$$

$$f. \Delta \hat{H} = \Delta \hat{H}_2 - \Delta \hat{H}_1 = 487.8 - 1276.7 = -788.9 \text{ Btu/lb}$$

Data from text
 $\Delta H_A = 1205.0$ ΔH_B use tables in pocket

	210°F		
	200°F	250°F	
5 psia	1148.3	1171.1	a. Enthalpy decrease
7 psia	1146.7	1170.2	
$\hat{V}_A=1.0451 \text{ ft}^3/\text{lb}$			
V_B	78.17	84.24	b. volume goes up
	38.88	41.96	
(h)	<u>40 psia and 267.24°F</u>	<u>70 psia/302°F</u>	<u>70 psia/304°F</u>
	sat steam/sat liquid	liquid	superheated steam

depending on heat supply

(continued)

(i) 2.5 ft³ tank of water @ 160 psia and 363.5°F. @ 160 psia 6363.5 total volume is occupied by sat steam

$$\dot{V}_{\text{steam}} = 2.834 \text{ ft}^3 / \text{lb} \Rightarrow m_{\text{steam}} = \frac{2.5}{2.834} = 0.88 \text{ lb}$$

$$\dot{V}_{\text{Liq/water}} = 0.0182 \text{ ft}^3 / \text{lb} \Rightarrow \dot{m}_{\text{water}} = (1 - m_{\text{steam}})$$

$$V_{\text{water}} = \frac{2.5}{2.834} \times 0.0182 = \boxed{0.016 \text{ ft}^3}$$

$$V_{\text{steam}} = 2.5 - 0.016 = 2.49 \text{ ft}^3$$

Of 5 lb H₂O assume x lb is sat steam (5 - x) lb is sat. water

$$x(2.834) + (5 - x)(0.0182) = 2.5$$

$$\Rightarrow x(2.834 - 0.0182) = 2.5 - 5(0.0182)$$

$$\Rightarrow x = \frac{2.5 - 0.910}{2.816} = 0.86 \text{ lb}$$

Yes, it is possible

(k) Enthalpy of 10 lb steam @ 100 psia = 9000 Btu

Enthalpy/lb steam @ 100 psia = 900 Btu

$$\Delta \hat{H}_{\text{steam}} @ 100 \text{ psia} = 1187.3 \text{ Btu}$$

$$\Delta \hat{H}_{\text{water}} @ 100 \text{ psia} = 298.43 \text{ Btu}$$

Let x be fraction of steam

(1 - x) is fraction of water

$$(1187.3)x + (1 - x) 298.43 = 900$$

$$x(1187.3 - 298.43) = 900 - 298.43 \quad x = \frac{601.57}{888.87} = 0.68$$

or **68%**

23.39

State 1

State 2

$$T = 400 \text{ K}$$

$$T = 900 \text{ K}$$

$$p = 100 \text{ kPa}$$

$$p = 100 \text{ kPa}$$

a. From the steam tables in SI units (interpolation required):

$$(1) \Delta \hat{H}_1 = 2729.8 \text{ kJ/kg}$$

$$(2) \Delta \hat{H}_2 = 3763.6 \text{ kJ/kg}$$

$$\Delta \hat{H} = 3763.6 - 2729.8 = 1033.8 \text{ kJ/kg}$$

$$\frac{1033.8 \text{ kJ}}{\text{kg}} \left| \frac{18 \text{ kg}}{\text{kg mol}} \right| \left| \frac{2 \text{ kg mol}}{\text{kg mol}} \right| = \boxed{3.7217 \times 10^4 \text{ kJ/2 kg mol}}$$

b. Using the table for the enthalpies of combustion gases:

$$(1) \Delta \hat{H} = 4284 \text{ J/g mol}$$

$$(2) \Delta \hat{H} = 22,760 \text{ J/g mol}$$

$$\Delta H = 22760 - 4284 = 1.848 \times 10^4 \text{ J/g mol} = 1.848 \times 10^4 \text{ J/kg mol}$$

$$\frac{1.848 \text{ kJ}}{\text{kg mol}} \left| \frac{2 \text{ kg mol}}{\text{kg mol}} \right| = \boxed{3.695 \times 10^4 \text{ kJ/2 kg mol}}$$

c. Using the heat capacity equation for steam:

$$\begin{aligned} \Delta H &= \int_{127^\circ - 273}^{627^\circ - 273} C_p dT = \int_{400}^{900} (33.46 + 0.6880 \times 10^{-2} T + 0.7604 \times 10^{-5} T^2 \\ &\quad - 3.593 \times 10^{-9} T^3) dT \\ &= 33.46(900 - 400) + \frac{0.6880 \times 10^{-2}}{2} (900^2 - 400^2) \\ &\quad + \frac{0.7604 \times 10^{-5}}{3} (900^3 - 400^3) - \frac{3.593 \times 10^{-9}}{4} (900^4 - 400^4) \\ &= 20,085 \text{ J/g mol} = 20,085 \text{ kJ/kg mol} \end{aligned}$$

(continued)

$$\frac{20,085 \times 10^4 \text{ kJ} / 2 \text{ kg mol}}{\text{kg mol}} = 4.017 \times 10^6 \text{ kJ} / 2 \text{ kg mol}$$

The steam tables are the most accurate value.

23.40

Basis: 5 ft³ vesselVapor = 4 ft³, Liquid = 1 ft³

Steam tables: Sat'd steam at 1000 psia

$$\hat{V}_v = 0.44596 \frac{\text{ft}^3}{\text{lb}}$$

$$\hat{V}_l = 0.02159 \frac{\text{ft}^3}{\text{lb}}$$

lb mass ft.

$$m_l = \frac{1 \text{ ft}^3}{0.02159 \text{ ft}^3} \frac{\text{lb}}{\text{ft}^3} =$$

46.32 0.838

$$m_v = \frac{4 \text{ ft}^3}{0.44596 \text{ ft}^3} \frac{\text{lb}}{\text{ft}^3} =$$

8.97 0.162

m_t = 55.29 1.000

$$\text{Quality} = 0.162$$

23.41

We will use the steam tables for this problem.

Basis: 1 lb of H₂O at 60°F

From steam tables (ref. temp. = 32°F):

$$\hat{H} = 28.07 \text{ Btu/lb at } 60^\circ\text{F}$$

$$\hat{H} = 1604.5 \text{ Btu/lb at } 1150^\circ\text{F and } 240 \text{ psig (254.7 psia)}$$

$$\Delta \hat{H} = (1604.5 - 28.07) = 1576.4 \text{ Btu/lb}$$

$$\Delta H = 1576(8.345) = 13,150 \text{ Btu/gal}$$

Note: The enthalpy value which has been used for liquid was taken from the steam tables for the saturated liquid under its own vapor pressure. Since the enthalpy of liquid water

changes negligibly with pressure, no loss of accuracy is encountered for engineering purposes if the initial pressure on the water is not stated.

23.42

Basis: 3 kg H₂O

The initial conditions are obtained from the SI steam tables for saturated liquid. Enthalpy is a function of the temperature and pressure, but the effect of pressure on liquid water under these conditions is negligible. Therefore the enthalpy of water at 300K and 101.3 kPa can be approximated by the enthalpy of saturated water at the same temperature but at the vapor pressure of 3.536 kPa.

The final conditions are presumably a state in which water is all vapor. A check of the steam tables show this assumption to be true.

At

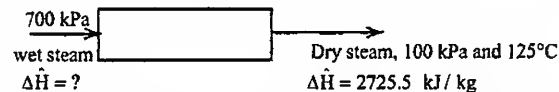
T(K)	p(kPa)	$\hat{H}(\text{kJ/kg})$
300	3.536	111.7
800	1500	3384.3

The enthalpy change is

$$\Delta H = \frac{3 \text{ kg} (3384.3 - 111.7) \text{ kJ}}{\text{kg}} = 9817.8 \text{ kJ}$$

23.43

Steady state flow process, no reaction



The energy balances reduces to $\Delta H=0$ for this process. At 700 kPa saturated (438.1K)

$$\Delta \hat{H}_L = 696.7 \text{ kJ / kg}$$

$$\Delta \hat{H}_v = 2763.1 \text{ kJ / kg}$$

Let x = vapor fraction

$$(1 - x)(696.7) + x(2763.1) = 2725.4$$

$$x = 0.98$$

Solutions Chapter 23

Solutions Chapter 23

23.44

Basis: 30 m³ at 101.3 kPa and 1100KUse $pV = nRT$ to calculate the number of moles

$$n = \frac{pV}{RT} = \frac{101.3 \text{ kPa} \cdot 30 \text{ m}^3}{1100 \text{ K} \cdot 8.314 \text{ kPa}(\text{m}^3)} \cdot \frac{1000 \text{ gmol}}{1 \text{ kg mol}}$$

$$n = 332.3 \text{ gmol}$$

Compound	%	g mol	$\Delta \hat{H}(\text{J/g mol})$		$\Delta H(\text{J})$	
			300K	1100K	Final	Initial
O ₂	6.2	20.6	790	26,940	16,274	554,964
H ₂ O	1.0	3.3	905	31,011	2987	102,336
CO ₂	12.3	40.9	986	39,802	40,327	1627902
N ₂	<u>80.5</u>	<u>267.5</u>	786	25,472	<u>210,255</u>	<u>6,813,760</u>
	100.0	332.3			269,843	9,098,963

$$\Delta H = \Delta H_{\text{final}} - \Delta H_{\text{initial}} = -8829 \text{ kJ}$$

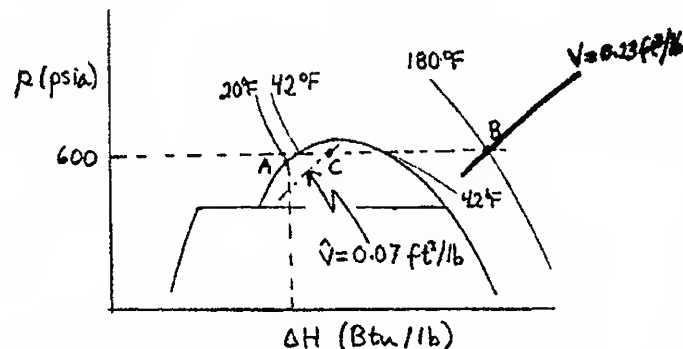
23.45

The amount of energy that the water gives up in cooling to 0°C is not enough to melt all the ice, since each gram of water will give up 209 J in cooling, while heating 1 g of ice to 0° and melting it requires that $2 \times 40 + 335 = 415 \text{ J}$ be expended (the heat capacity of ice is 2J/(g) (°C)).

23.46

[Yes] 40°F and saturated liquid is an arbitrary reference state for enthalpy that can be assigned a value of zero. Only enthalpy changes can be computed using the chart; the enthalpy itself cannot be determined.

23.47



$$a-1: \hat{V} \approx 0.23 \text{ ft}^3/\text{lb}$$

a-2: gas

b-1: 42°F

b-2: mixture of liquid and vapor

23.48

Basis: 1 lb CO₂ Ref is -40°F satd. liquid

$$\Delta \hat{U} = \Delta \hat{H} - \Delta(p\hat{V}) = (\Delta \hat{H}_{40/40} - \Delta \hat{H}_{\text{ref}}) - [(p\hat{V})_{40/40} - (p\hat{V})_{\text{ref}}]$$

$$\Delta(pV) = \frac{40 \text{ lb}_f}{\text{in}^2} \cdot \frac{3.2 \text{ ft}^3}{\text{lb}_m} \cdot \frac{144 \text{ in}^2}{\text{ft}^2} \cdot \frac{\text{Btu}}{(778 \text{ ft})(\text{lb}_f)} - \frac{160 \text{ lb}_f}{\text{in}^2} \cdot \frac{0.0148 \text{ ft}^3}{\text{lb}_m} \cdot \frac{144 \text{ in}^2}{\text{ft}^2} \cdot \frac{\text{Btu}}{(778 \text{ ft})(\text{lb}_f)}$$

$$= 23.69 - 0.44 = 23.25 \text{ Btu/lb}_m$$

$$\Delta \hat{U} = (161 - 0) - 23.25 = 138 \text{ Btu}$$

23.49

Basis: 1 g mol CO₂

$$\Delta H = m \int_{50^\circ\text{C}}^{100^\circ\text{C}} (a + bT + cT^2 + dT^3) dT$$

$$\Delta H = m \left[a(100 - 50) + \frac{b}{2}(100^2 - 50^2) + \frac{c}{3}(100^3 - 50^3) + \frac{d}{4}(100^4 - 50^4) \right]$$

$$\Delta H = 1 \text{ g mol} \left[\frac{36.11(100 - 50) + \frac{4.233 \times 10^{-2}}{2}(100^2 - 50^2) - \frac{2.887 \times 10^{-5}}{3}(100^3 - 50^3) + \frac{7.464 \times 10^{-9}}{4}(100^4 - 50^4)}{4} \right]$$

$$\Delta H = 1956 \text{ J}$$

From the CO₂ chart $\Delta H \cong 198.178 = 20 \text{ Btu/lb}$ or 2040 J/g mol . From the enthalpy tables (interpolating) $\Delta H = 1957 \text{ J/g mol}$. The CD gives 2038 J/g mol .

23.50

$$\Delta H = 10(\Delta \hat{H}_2 - \Delta \hat{H}_1) = 10(86 - 288) = -2020 \text{ Btu}. \text{ The CD gives } -1962 \text{ J.}$$

23.51

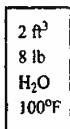
Assume the temperature is 80°F, and the propane is saturated liquid and vapor. The corresponding pressure is the saturation pressure, namely about 2.3 atm. Another temperature would correspond to another pressure. After 80% of the propane is used, the conditions are still saturated liquid-vapor mixture at 80°F and 2.3 atm.

Solutions Chapter 24

24.1

(1) System is the tank (3)

(2) Closed, unsteady state process



The 8 lb H₂O occupy 0.129 ft³ hence the rest of space is vapor. We will ignore the initial vapor (see note at end of solution) (4a)

Basis: 8 lb H₂O

(4) { Initial data for H₂O are (satd liquid)
 $T = 100^\circ\text{F}$ $\hat{V} = 0.01613 \text{ ft}^3/\text{lb}$
 $p = 0.9487 \text{ psia}$ $\Delta\hat{H} = 67.97 \text{ Btu/lb}$ if neglect vapor
 Basis: 1 hr

(5) { The energy balance is
 $\Delta E = [\Delta U + \Delta PE + \Delta KE]_{\text{inside}} = Q + W - \Delta H - \Delta PE - \Delta KE$
 no change in PE or KE inside no mass transfer
 $\Delta U = W = \Delta H - \Delta(pV) = \Delta H - V\Delta p$

$$(6) W = \frac{0.25 \text{ hp}}{1(\text{hp})(s)} \left| \frac{0.7068 \text{ Btu}}{1(\text{hp})(s)} \right| \frac{3600s}{1 \text{ hr}} = +636 \text{ Btu}$$

This proves to be negligible quantity



$$(7a) 636 = \Delta\hat{H}_{\text{final}}(8) - \frac{2 \text{ ft}^3}{1 \text{ ft}^3} \left| \frac{(p_{\text{final}} - 0.9487) \text{ lb}_f}{\text{in}^2} \right| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \left| \frac{1 \text{ Btu}}{748(\text{ft})(\text{lb}_f)} \right|$$

Solutions Chapter 24

(8) { Since p_{final} , $\hat{V}_{\text{final}}$, and $\Delta\hat{H}_{\text{final}}$ are in the tables, you have to get a $\Delta\hat{H}_{\text{final}}$, and $\hat{V}_{\text{final}}$ vapor given an assumed p_{final} that satisfy the equation. $\Delta\hat{H}_{\text{final}}$ will be composed of saturated liquid and vapor. $\Delta\hat{H}_L(8-m) + \Delta\hat{H}_v(m) = \Delta\hat{H}_{\text{final}}$, $m = \text{lb vapor}$. (7c)

(7b) $2 \text{ ft}^3 = \hat{V}_L(8-m) + \hat{V}_v(m)$.
 $\hat{V}_L, \hat{V}_v, \Delta\hat{H}_L, \Delta\hat{H}_v$, and p_{final} are all related in the steam tables.

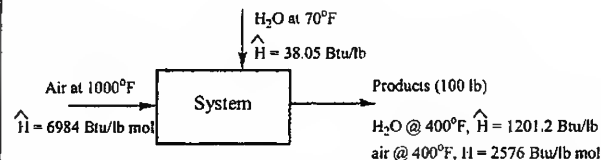
* $\hat{V}$ of saturated vapor = 350.8 ft³/lb so that 1.87 ft³ represents 0.0053 lb, a negligible amount relative to 2 lb.

24.2

(1) The system is the mixing point of the 1000°F "air" and water at 70°F

(2) Open system

(3) and (4)



The enthalpies of water come from the steam tables. The properties of air come from the tables in Appendix D7 (with interpolation). The reference temperature for the enthalpy is 32°F.

(5) $\Delta E = [\Delta U + \Delta PE + \Delta KE]_{\text{inside}} = Q + W - \Delta H - \Delta PE - \Delta KE$

• 0 because steady state

(continued)

Solutions Chapter 24

- Q is assumed to be 0 because time is short in transit
- $W = 0$ (none specified)
- $\Delta KE = \Delta PE = 0$ none with mass flow

Thus $\Delta H = 0$ or $\Delta H_{out} = \Delta H_{in}$

(6) The units in the balance will be Btu and lb

$$(n_{air})\Delta\hat{H}_{air} + (n_{H_2O})\Delta\hat{H}_{H_2O}(g) = (n_{air})\Delta\hat{H}_{air} + (n_{H_2O})\Delta\hat{H}_{H_2O} \quad (e)$$

@ 400°F @ 400°F @ 1000°F (a) 70°F

$$\frac{(100)(2576)}{29} + (m_{H_2O})(1238.9) = (100)\frac{(6984)}{29} + m_{H_2O}(38.05)$$

24.3

You can write one material balance for each unit and one energy balance for each unit, or a total of 6. You can write numerous equations but only 6 are independent.

24.4

The equation is

$$\Delta E = \Delta(U + PE + KE)_{inside} = Q + W - \Delta(H + PE + KE)_{flow}$$

- (a) $W = 0$
- (b) $Q = 0$
- (c) $\Delta(KE)_{flow} = 0$
- (d) $\Delta PE \neq 0$

Solutions Chapter 24

24.5

The exit enthalpies are all the same since the states of p and T are the same. The turbine is the only process that yields work.

24.6

a. $(E_2 - E_1) = -\Delta[\hat{H} + \widehat{KE} + \widehat{PE}]m + Q + W$ for all parts of this problem

1. Ignore $\widehat{PE}$; $\Delta\widehat{PE} = 0$
2. $\Delta\widehat{KE}$ is small so $\Delta\widehat{KE} = 0$ (or it can be included)
3. No reaction
4. $W = 0$
5. $(E_2 - E_1) = 0$; steady state

$$\Delta H = Q$$

- b.
1. Ignore $\widehat{PE}$; $\Delta\widehat{PE} = 0$
 2. No reaction
 3. $W = 0$
 4. $(E_2 - E_1) = 0$; steady state
 5. $Q = 0$

$$-\Delta[\hat{H} + \widehat{KE}]m = 0$$

- c. 1. Ignore $\widehat{PE}$; $\Delta\widehat{PE} = 0$

(continued)

Solutions Chapter 24

2. $\widehat{\Delta KE} = 0$
3. No reaction
4. $(E_2 - E_1) = 0$; steady state
5. $Q = 0$ (assume)

$$\boxed{\Delta H = W}$$

- d.
1. Ignore $\widehat{PE}$; $\widehat{\Delta PE} = 0$
 2. No reaction
 3. $(E_2 - E_1) = 0$; steady state (may be not the $\widehat{KE}$)
 4. $Q = 0$ (assumed)

$$\boxed{\Delta[\widehat{H} + \widehat{KE}]m] = W}$$

24.7

General balance is

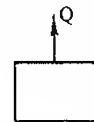
$$\Delta E = [\Delta U + \Delta KE + \Delta PE]_{\text{inside}} = -\Delta[(\widehat{H} + \widehat{KE} + \widehat{PE})m] + Q + W$$

(1) (2) (3) (4) (5) (6) (7) (8)

Assume all reactants are in bomb at start of reaction.

Solutions Chapter 24

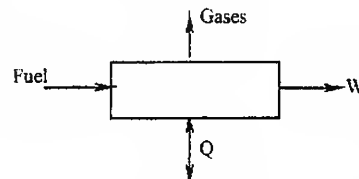
a.



- | | | | | |
|---|-----------------------------------|--|-----------------------------|--|
| 1 | ΔU retain because changes | 7 | Q retain | |
| 2 | ΔKE delete - no change | 8 | W delete (fixed boundary) | |
| 3 | ΔPE delete - no change | | | |
| 4 | } ΔH | | | |
| 5 | | } ΔKE delete as no mass flow in or out | | |
| 6 | | | } ΔPE | |

$$\text{Result: } \Delta U = Q$$

b.



$$\Delta H = Q - W$$

- | | | | |
|---|---------------------------------------|---|--------------------------|
| 1 | } $\Delta E = 0$ because steady state | 5 | delete as negligible |
| 2 | | 6 | delete not a factor |
| 3 | | 7 | Q keep |
| 4 | ΔH keep | 8 | W keep (electric work) |

$$\text{Result: } \Delta H = Q + W$$

(continued)

Solutions Chapter 24

c.

- | | | | |
|---|-------------------------------|---|-----------------------------------|
| 1 | } $\Delta U = 0$ steady state | 5 | ΔKE delete negligible |
| 2 | | 6 | ΔPE delete not applicable |
| 3 | | 7 | $Q = 0$ insulated applicable |
| 4 | ΔH is kept | 8 | $W = 0$ no work done |

Result: $\Delta H = 0$

24.8

Closed, unsteady state process

Basis: 10 lb steam @ 300 psia and 480°F

$Q + W = \Delta U$ for the closed system. $W = 0$

$$\left. \begin{array}{l} \Delta \hat{H} = 1246.6 \text{ Btu/lb} \\ \hat{V} = 1.7164 \text{ ft}^3/\text{lb} \end{array} \right\} \text{superheated initially}$$

$$\hat{U} = 1150.38 \text{ Btu/lb}$$

After cooling to 30 psia, the steam is saturated and liquid forms. Thereafter the steam proceeds at constant total and specific volume.

Ignore the volume of the liquid. Final conditions are 30 psia and 17.164 ft³ for the residual vapor

$\Delta \hat{H}_L = 218.33 \text{ Btu/lb}$	$\hat{V}_L = 0.0170 \text{ ft}^3/\text{lb}$	$\hat{U}_L = 218.81 \text{ Btu/lb}$
$\Delta \hat{H}_V = 1164.0 \text{ Btu/lb}$	$\hat{V}_V = 13.763 \text{ ft}^3/\text{lb}$	$\hat{U}_V = 1087.8 \text{ Btu/lb}$

Solutions Chapter 24

$$\frac{1 \text{ lb}}{13.763 \text{ ft}^3} \left| \frac{17.164 \text{ ft}^3}{1} \right| = 1.25 \text{ lb vapor remains}$$

Note: $\frac{0.0170 \text{ ft}^3}{\text{lb}} \left| \frac{8.75 \text{ lb}}{1} \right| = 0.15 \text{ ft}^3$ of liquid exists, hence

the vapor volume is 17.164 – 0.15 = 17.01 ft³, and

$$\frac{1 \text{ lb}}{13.763 \text{ ft}^3} \left| \frac{17.01 \text{ ft}^3}{1} \right| = 1.24 \text{ lb vapor remains}$$

We could now correct for the liquid volume, but will not. The value of Q is

$$Q = [1.25(1087.8) + (10 - 1.25)(218.81)] - 10(1150.38) = \boxed{-8229.5 \text{ Btu}}$$

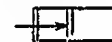
The temperature is the saturation temperature of $\boxed{250.3^\circ\text{F}}$

Note: If you do not have access to $\hat{U}$ values, calculate $\hat{U} = \hat{H} - p\hat{V}$.

24.9

Unsteady state, closed, isothermal process at 25°C

Basis: 1 kg CO₂



$$\begin{array}{l} p_1 = 550 \text{ kPa} \\ T_1 = 25^\circ\text{C} \end{array}$$

$$\begin{array}{l} p_2 = 3500 \text{ kPa} \\ T_2 = 25^\circ\text{C} \end{array}$$

From CO ₂	$\hat{V}_1 = 0.10 \text{ m}^3/\text{kg}$	$\hat{V}_2 = 0.0125 \text{ m}^3/\text{kg}$	(continued)
chart	$\Delta \hat{H} = 205 \text{ kJ/kg}$	$\Delta \hat{H}_2 = 170 \text{ kJ/kg}$	

Solutions Chapter 24

(converted to SI units)

Energy balance

$$\Delta E = \Delta[(U + PE + KE)]_{\text{inside}} = Q + W - \Delta(H + PE + KE)$$

$$\Delta U = Q + W = \Delta H - \Delta(pV) \text{ so } Q = \Delta H - \Delta(pV) - W$$

$$\Delta H = (170 - 205)(1) = -35 \text{ kJ}$$

$$W = 4.106 \text{ kJ}$$

$$\Delta(pV) = \left[\frac{3500 \text{ kPa}}{1 \text{ kg}} \left| \frac{0.0125 \text{ m}^3}{\text{kg}} \right| - \frac{550 \text{ kPa}}{1 \text{ kg}} \left| \frac{0.10 \text{ m}^3}{\text{kg}} \right| \right] \left[\frac{10^3 \frac{\text{N}}{\text{m}^2}}{1 \text{ kPa}} \left| \frac{1 \text{ J}}{1(\text{N})(\text{m})} \right| \right] = -11.25 \text{ kJ}$$

$$Q = (-35) - (-11.25) - 4.106 = \boxed{-27.86 \text{ kJ / kg CO}_2}$$

(removed)

24.10

This is an unsteady-state closed process. The energy balance reduces to

$$\Delta E = \Delta U + \Delta PE + \Delta KE = Q + W \quad \Delta PE = \Delta KE = 0$$

$$Q = \Delta U = U_2 - U_1 = \Delta H - \Delta(pV) = \Delta H - (p_2 V_2 - p_1 V_1)$$

where 2 (327.8°F) is the final state and 1 (406°F) is the initial state

Get the data from the CD in the back of the book. The final state is saturated conditions. $\hat{U}$ and $\hat{H}$ are in Btu/lb and $\hat{V}$ is ft³/lb.

Solutions Chapter 24

$\hat{H}_{1,L} = 381.65$	$\hat{H}_{1,V} = 1202.2$	$\hat{H}_{2,L} = 298.5$	$\hat{H}_{2,V} = 1187.5$
$\hat{U}_{1,L} = 380.72$	$\hat{U}_{1,V} = 1116.7$	$\hat{U}_{2,L} = 298.2$	$\hat{U}_{2,V} = 1105.5$
$\hat{V}_{1,L} = 0.019$	$\hat{V}_{1,V} = 1.743$	$\hat{V}_{2,L} = 0.0177$	$\hat{V}_{2,V} = 4.433$

From the steam tables, get the initial amount of steam and use as the basis:

$100 \left(\frac{1}{1.743} \right) = 57.4 \text{ lb}$ ignoring the liquid volume. (If you do not, you have to get the average volume) and get the final state. Let y = the fraction of liquid at 100 psia

$$\hat{V}_{\text{liquid}} = 0.0177 \text{ ft}^3/\text{lb}, \hat{V}_{\text{vapor}} = 4.433 \text{ ft}^3/\text{lb}$$

Basis: 1 lb water

$$y(0.0177) + (1-y)(4.433) = 1.74 \quad y = 0.6095 \text{ lb (liquid)} \quad x = 0.3905 \text{ lb (vapor)}$$

Use values of $\hat{U}$ from the CD to calculate Q . Otherwise you have to calculate $\Delta(pV)$.

$$Q = [(0.6095)(298.2) + (0.3905)(1105.5)] - [(116.7)(1)]$$

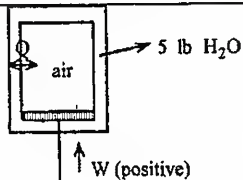
$$Q = -503 \frac{\text{Btu}}{\text{lb}} \text{ or } \boxed{Q = -2.71 \times 10^4 \text{ Btu}}$$

24.11

This is an unsteady state process in a closed system, or a closed system with air and surroundings with water. From the latter viewpoint the system is the air, and $\Delta U = Q + W$ where Q is the heat transfer to the water from the air.

(continued)

Solutions Chapter 24



For the system of the air

$$Q + W = \Delta E = \Delta U + \Delta P + \Delta K = \Delta H - \Delta(pV)$$

For the water:

$Q = \Delta H - \Delta(pV)$ but $\Delta(pV)$ is negligible for liquid water so that

$$Q = \Delta H = 5 \int_T^{T+2.3} C_p dT = 5 C_p (T + 2.3 - T) \text{ for constant } C_p.$$

(or use the steam tables)

$$C_p = 8.0 \frac{\text{Btu}}{(\text{lb mol})(^\circ\text{F})}$$

$$Q = 8.0 \frac{\text{Btu}}{(\text{lb mol})} \left| \frac{2.3^\circ\text{F}}{1} \right| \left| \frac{1 \text{ lb mol H}_2\text{O}}{18 \text{ lb H}_2\text{O}} \right| \left| \frac{5 \text{ lb H}_2\text{O}}{1} \right| = 5.11 \text{ Btu}$$

Q is removed from the air, so for the system comprised of the air, $Q = -5.11 \text{ Btu}$.

For the system of the air

$$W = \frac{12,500(\text{ft})(\text{lb}_f)}{1(\text{ft})(\text{lb}_f)} \left| \frac{0.0012854 \text{ Btu}}{1} \right| = 16.07 \text{ Btu}$$

W is positive when the surroundings do work on the system of the air.

Solutions Chapter 24

Basis: 3 ft^3 air (not essential)

$$\Delta U = -5.11 \text{ Btu} + 16.07 \text{ Btu} = \boxed{10.96 \text{ Btu}}$$

24.12

Closed system

The system initially is like the figure, but since $p_A > p_B$, the plug moves



to the right. The energy balance here is $Q + W = \Delta E = \Delta U$. Since $Q = 0$ and $W = 0$, ΔU must be 0. ΔPE and $\Delta KE = 0$.

24.13

Closed system

The energy balance reduces to $Q + W = \Delta E = \Delta U + \Delta PE + \Delta KE$

$Q = 0$, $W = 0$, $\Delta PE = 0$, $\Delta KE = 0$, hence $\Delta U = 0$.

24.14

Steps 1, 2, 3 and 4

Get the needed properties from the CO_2 chart or tables (Be sure to use the same reference value). Let m_{CO_2} be the mass of CO_2 in the cylinder at the final state, $\hat{V}$ is the specific volume, $\hat{U}_{\text{final}}$ is the specific internal energy of the CO_2 at the end of the filling, and $\hat{H}_m$ is the specific enthalpy of the CO_2 in the pipeline.

(continued)

Solutions Chapter 24

At 200 psia, 40°F, $\hat{H} \approx 153$ Btu/lb and $\hat{V} \approx 0.57$ ft³/lb

Step 5

Basis: 3 ft³ of CO₂ @ 200 psia (final conditions)

System: The cylinder (open system, unsteady state)

Steps 6 and 7:

Unknowns: $\hat{V}_{\text{CO}_2}$, m_{CO_2} , T_{CO_2}

Equations: energy balance, enthalpy chart

We need two points on the $p-\hat{H}$ chart to fix the conditions in the cylinder. The energy balance reduces to ($W = 0$, Q assumed to be 0)

$$\Delta U = -\Delta H$$

which gives one point:

$$m_{\text{CO}_2}(\hat{U}_{\text{final}}) - m_{\text{initial}}(\hat{U}_{\text{initial}}) = m_{\text{in}}(\hat{H}_{\text{in}}) - m_{\text{out}}(\hat{H}_{\text{out}})$$

$$m_{\text{initial}} = 0 \quad m_{\text{out}} = 0 \quad m_{\text{CO}_2} = m_{\text{in}}$$

$$\hat{U}_{\text{final}} = \hat{H}_{\text{in}} = 153 \text{ Btu/lb}$$

The other point is the pressure $p = 200$ psia. Unfortunately the CO₂ chart is $p-\hat{H}$ and not $p-\hat{U}$, thus requiring a trial and error solution. Assume a T , lookup $\hat{V}$, and calculate $\hat{U} = \hat{H} - p\hat{V}$ (ignore $p\hat{V}$ at the reference state of -40°F).

When $\hat{U} = 153$ Btu/lb, then you have determined T . If you used tables of p vs $\hat{U}$ in a handbook, the calculations would be easier.

Solutions Chapter 24

		$\hat{H}$	p	$\hat{V}$	$\hat{U}$
Assume $T = 160^\circ\text{F}$.	Then $\hat{H} - p\hat{V} =$	182	-(200)(0.68)	(0.185)	= 157
$T = 140^\circ\text{F}$.	Then $\hat{H} - p\hat{V} =$	178	-(200)(0.70)	(0.185)	= 153

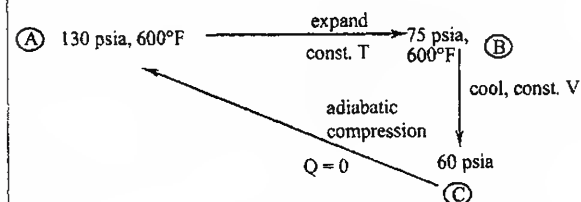
The calculates are quite approximate but

$$T = 140^\circ\text{F} \quad m_{\text{CO}_2} = \frac{3 \text{ ft}^3}{0.70 \text{ ft}^3/\text{lb}} = 4.3 \text{ lb}$$

24.15

Basis: 1 lb steam

Closed system; hence $Q + W = \Delta E = \Delta U$



Basis: 1 lb steam

Note: The CD will result in slightly different values for $\Delta\hat{H}$.

$$\text{A} \rightarrow \text{B} : \Delta\hat{H} = 1329.6 - 1326.1 = 3.5 \text{ Btu/lb}$$

Use the steam tables or the CD directly for U , or calculate

$$\Delta\hat{U} = \Delta\hat{H} - \Delta(p\hat{V}) =$$

(continued)

Solutions Chapter 24

$$= 3.5 - \left[\frac{75 \text{ lb}}{\text{in}^2} \left| \frac{8.319 \text{ ft}^3}{\text{lb}} - \frac{130 \text{ lb}}{\text{in}^2} \left| \frac{4.760 \text{ ft}^3}{\text{lb}} \right| \right] \left[\frac{144 \text{ in}^2}{\text{ft}^2} \left| \frac{1 \text{ Btu}}{778 (\text{ft}) (\text{lb}_f)} \right| \right]$$

$$= 3.5 - .95 = \boxed{2.5 \text{ Btu/lb}} \quad \dot{Q} = ? \quad \dot{W} = ?$$

$\dot{W} = - \int p dV$ but pV relation is not known.

$\textcircled{B} \rightarrow \textcircled{C}$: $\boxed{W=0}$ (at constant volume)

$$\Delta \hat{H} = 1232.7 - 1329.6 = \boxed{-96.9 \text{ Btu/lb}}$$

$$\Delta \hat{U} = -96.9 \left[\frac{60 \left| \frac{8.319}{\text{lb}} - \frac{75 \left| \frac{8.319}{\text{lb}} \right|}{\text{in}^2} \right] \left[\frac{144 \text{ in}^2}{\text{ft}^2} \left| \frac{1 \text{ Btu}}{778 (\text{ft}) (\text{lb}_f)} \right| \right] = -73.8 \text{ Btu/lb}$$

$$\dot{Q} = \Delta \hat{U} = \boxed{-73.8 \text{ Btu/lb}}$$

$\textcircled{C} \rightarrow \textcircled{A}$: $\dot{Q} = 0$ so $\dot{W} = \Delta \hat{U} = \Delta \hat{H} - \Delta(p\hat{V})$

$$\Delta \hat{H} = 1326.1 - 1232.7 = 93.4 \text{ Btu/lb}$$

$$\Delta p\hat{V} = \left[\frac{130 \left| \frac{4.760}{\text{lb}} - \frac{60 \left| \frac{8.319}{\text{lb}} \right|}{\text{in}^2} \right] \left[\frac{144}{778} \right] = 22.15 \text{ Btu/lb}$$

$$\dot{W} = 93.4 - 22.15 = \boxed{71.3 \text{ Btu/lb}} \quad \Delta U = 93.4 - 22.15 = \boxed{71.3 \text{ Btu/lb}}$$

24.16

Closed system, unsteady state; system is both tanks together

Basis: 1 m^3 dry steam, 350 K , 40 kPa , $\hat{V} = 4.005 \text{ m}^3/\text{kg}$, equivalent to $\frac{1 \text{ kg}}{4.005} \cong 0.25 \text{ kg}$

Solutions Chapter 24

a. $W = 0$ because the system boundary is fixed.

b. The energy balance reduces to $Q = \Delta U$

Initial Data

Final Data

$$\hat{V} = 4.005 \text{ m}^3 / \text{kg}$$

$$V = 2 \text{ m}^3$$

$$\Delta \hat{H} = 2638.2 \text{ kJ/kg}$$

$$\hat{V} = \frac{2 \text{ m}^3}{0.25 \text{ kg}} = 8.01 \text{ m}^3 / \text{kg}$$

$$\Delta \hat{U} = 2478.0 \text{ kJ/kg}$$

$$T = 350 \text{ K}$$

$$T = 350 \text{ K}$$

At $\hat{V} = 8.044$, $T = 350 \text{ K}$, $\Delta \hat{H} = 2641.4$ and $\Delta \hat{U} = 2480.6 \text{ kJ/kg}$

$$\dot{Q} = 2480.6 - 2478.0 = 2.6 \text{ kJ/kg}$$

$$(2.6) (0.25) = \boxed{0.65 \text{ kJ}}$$

24.17

Basis: 0.1 kg steam



Final pressure = 700 kPa

Batch process, unsteady state. The system is the gas plus the piston.

(continued)

Solutions Chapter 24

(a) The work can be calculated from $\int p dV$ if some assumptions are made about the process. No information is given about the process other than "slowly". Assume the work done (against the atmosphere) is carried out at constant atmospheric pressure. Then

$$W = -p\Delta V$$

Initial conditions

$V = 0$ at the start of the expansion (or could calculate $\hat{V}$ initially ($\hat{V} = 0.2995 \text{ m}^3/\text{kg}$) but ΔV is what counts so that letting $V = 0$ initially is ok)

(d) Change in volume of the system

$$\text{added } V = \frac{(80 \text{ cm})(118 \text{ cm}^2)}{(100 \text{ cm})^3} \frac{1 \text{ m}^3}{1000} = 0.00944 \text{ m}^3$$

$$W = - \frac{101.3 \text{ kPa} | 0.00944 \text{ m}^3}{(1 \text{ kPa})(\text{m}^3)} \frac{1 \text{ J}}{1000} = \boxed{-9.56 \text{ J}}$$

(work done by system; does not include raising of the piston)

To get Q apply the energy balance to the gas

$$Q + W = \Delta U + \Delta PE_{\text{piston}}$$

To get ΔU , have to determine $\hat{U}_{\text{final}}$ and $\hat{U}_{\text{initial}}$.

At 650 K and 1000 kPa:

$$\hat{V}_{\text{initial}} = 0.2955 \text{ m}^3/\text{kg} \quad \hat{U}_{\text{initial}} = 2918.8 \text{ kJ/kg}$$

At 700 kPa and $\hat{V}_{\text{final}}$:

$$\begin{aligned} \text{Initial volume} &= (0.2995)(0.1) = 0.02995 \text{ m}^3 \\ \text{Added volume} &= 0.00944 \text{ m}^3 \\ \text{Final volume} &= 0.03939 \text{ m}^3 \end{aligned}$$

Solutions Chapter 24

$$\hat{V}_{\text{final}} = \frac{0.03939}{0.1} = 0.394 \text{ m}^3/\text{kg}$$

At these conditions:

$$(b) \quad \hat{U}_{\text{final}} = 2841.9 \text{ kJ/kg and } \boxed{T_{\text{final}} = 600 \text{ K}}$$

$$\Delta PE = PE_2 - PE_1 = mgh_2 - mgh_1$$

$$= \frac{0.46 \text{ kg}}{1} \frac{9.8 \text{ m}}{\text{s}^2} \frac{0.80 \text{ m}}{1} \frac{1(\text{J})(\text{s}^2)}{(\text{kg})(\text{m}^2)} = 3.61 \text{ J}$$

$$(c) \quad Q = (2841.9 - 2918.8)(0.1) + 3.61 - (-9.56) = \boxed{5.48 \text{ J}}$$

24.18

Pick the room as the system. The simplified form of the energy balance is (for no mass flow):

$$\Delta E = \Delta U = Q + W = \Delta U$$

where $Q = 0$ (room is insulated)

W = the electrical energy provided freezer through the system boundary and is positive. (No volume change occurs). Hence $\Delta U = C_v \Delta T$ is positive and ΔT is positive; i.e. the temperature increases.

24.19

Basis: 1 hour

Assume: (1) Thermal properties are constant
(2) No work is done

(continued)

Closed unsteady-state system

The energy balance is

$$\Delta U = Q \quad \Delta U \text{ includes "heat of respiration" and change in temperature}$$

The mass of potatoes is: $(52)(24)(20) = 24,960 \text{ kg}$ The mass of the boxes is: $(52)(24)(2.1) = 2,621 \text{ kg}$ Respiration = $(24,960 \text{ kg})(0.035 \text{ W/kg}) = 873.6 \text{ W}$

$$\Delta \dot{U}_{\text{potato}} = \frac{m C_p \Delta T}{\Delta t} = \frac{24,960 \text{ kg}}{\Delta t} \left| \frac{3.05 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right| \frac{-0.3^\circ\text{C}}{\text{m}} = -22,838 \text{ kJ/hr}$$

$$(-6344 \text{ W})$$

$$\Delta \dot{U}_{\text{boxes}} = \frac{m C_p \Delta T}{\Delta t} = \frac{2,621 \text{ kg}}{\Delta t} \left| \frac{1.7 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right| \frac{-0.3^\circ\text{C}}{\text{m}} = -1,337 \text{ kJ/hr}$$

$$(-371 \text{ W})$$

$$Q = 873.6 - [6344 + 371] = -5842 \text{ W} \quad \boxed{5.84 \text{ kW energy is removed}}$$

24.20

(a) Assume steady state flow process. The system includes the orifice.

$$\Delta U = Q + W - \Delta H - \Delta PE - \Delta KE$$

$$\Delta U = 0 \text{ (steady state)} \quad \Delta PE = 0$$

$$Q = 0 \text{ (adiabatic essentially)} \quad \Delta KE \approx 0$$

$$\boxed{W = 0 \text{ (no work done)}}$$

Final simplified equation: $\Delta H = 0$

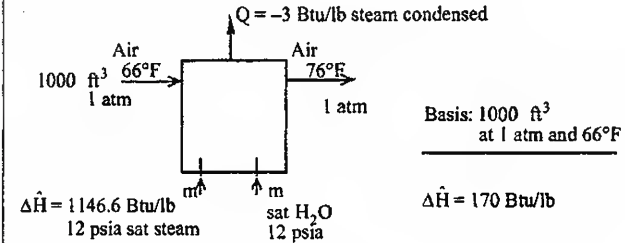
$$(b) \quad \Delta KE \approx 0, Q = 0, \Delta PE = 0, \Delta U = 0$$

$$\boxed{\Delta H = W}$$

$$(c) \quad \Delta E = 0 \quad \Delta PE = \Delta KE = 0 \quad \boxed{\Delta H = 0} \quad W = 0, Q = 0$$

24.21

Steady state, open system



Basis: 1 hour

$$-\Delta \hat{H} + Q + \dot{W} = 0$$

Steady state, no PE, no KE, no W

$$Q = \Delta H$$

$$Q = \frac{-3 \text{ Btu}}{\text{lb steam}} \left| \frac{\text{m lb steam}}{\text{lb steam}} \right| = -3m$$

$$-3m = (170 - 1146.6) \frac{\text{Btu}}{\text{lb steam}} \left| \frac{\text{m}}{\text{lb steam}} \right| + \int_{66}^{76} (6.900 + 0.02884 \times 10^{-2} T) \quad (\text{continued})$$

Solutions Chapter 24

$$+ 0.02429 \times 10^{-5} T^2 - 0.0852 \times 10^{-9} T^3) dT$$

$$= 6.900(76-66) + \frac{0.02884 \times 10^{-2}}{2} (76^2 - 66^2) + \frac{0.02429 \times 10^{-5}}{3} (76^3 - 66^3)$$

$$- \frac{0.08052 \times 10^{-9}}{4} (76^4 - 66^4) = 69.03 \text{ Btu / lb mol}$$

$$n = \frac{pV}{RT} = \frac{1 \text{ atm} \cdot 1000 \text{ ft}^3}{0.7302 \left(\frac{\text{ft}^3}{\text{lb mol}} \right) (531^\circ \text{R})} = 2.58 \text{ lb mol}$$

$$973.6 \text{ m} = 69.03 (2.58)$$

$$m = 0.18 \text{ lb steam}$$

24.22

Assume steady state, open system, no change in height or velocity, and $Q = 0$.

Basis: 1 hr

$$10 \text{ atm} = 1013 \text{ kPa}$$

$$\Delta E = -[(\Delta \hat{H} + \Delta \hat{K} + \Delta \hat{P})m] + Q + W$$

$$W = \Delta \hat{H} m = (\Delta \hat{H}_2 - \Delta \hat{H}_1) n$$

IC

FC

$$p: 1013 \text{ kPa} \sim 1000 \text{ kPa}$$

$$p: 101.3 \text{ kPa saturated}$$

$$T: 500 \text{ K}$$

$$T = 373.1 \text{ K}$$

$$\Delta \hat{H}_1: 2890.2 \text{ kJ/kg}$$

$$\Delta \hat{H}_2: 2675.6 \text{ kJ/kg}$$

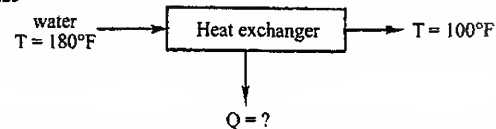
Solutions Chapter 24

$$\dot{W} = (2675.6 - 2890.2) (700) = -150,200 \text{ kJ/hr}$$

(work done by the system per hour)

$$= \frac{-150,200 \text{ kJ}}{\text{hr}} \left| \frac{(s)(1W)}{1J} \right| \frac{1 \text{ hr}}{3600s} = \boxed{-41.7 \text{ kW}}$$

24.23



Assume: Steady-state, open system with no change in elevation (no potential energy), and constant velocity (no $\Delta \hat{K}E$). No work is done on or by the system.

Basis: 1 hour

$$\begin{array}{cccc} 0 & 0 & 0 & 0 \\ \downarrow & \downarrow & \downarrow & \downarrow \\ \Delta E = -[\Delta \hat{H} - \Delta \hat{K}E + \Delta \hat{P}E]m + Q + W \end{array}$$

$$Q = \Delta \hat{H} m = (\Delta \hat{H}_2 - \Delta \hat{H}_1) n$$

From the steam tables for the liquid water

$$\Delta \hat{H}_1 = 148.00 \text{ Btu/lb} \quad \hat{V}_{180^\circ \text{F, liquid}} = 0.01651 \text{ ft}^3/\text{lb}$$

$$\Delta \hat{H}_2 = 67.999 \text{ Btu/lb}$$

Amount of water is

(continued)

Solutions Chapter 24

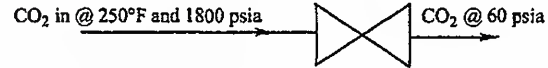
$$m = \frac{1}{0.01651} \frac{\text{lb}_m}{\text{ft}^3} \left| \frac{100 \text{ ft}^3}{\text{hr}} \right| = 6057 \frac{\text{lb}_m}{\text{hr}} \text{ enter and leave}$$

$$Q = (67.999 - 148.00) \frac{\text{Btu}}{\text{lb}_m} \left| \frac{6057 \text{ lb}_m}{\text{hr}} \right| = \boxed{-4.85 \times 10^5 \frac{\text{Btu}}{\text{hr}}}$$

(heat removed)

24.24

Steady state, open system



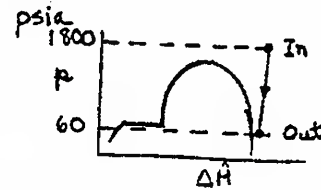
$$Q + W = -\Delta H \text{ and } Q = W = 0 \text{ so } \Delta H = 0$$

Point A is given. See chart. Point B is determined as follows:

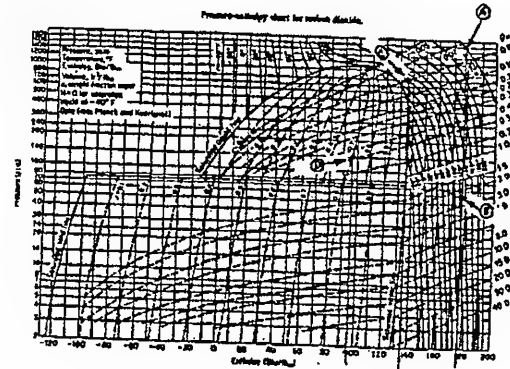
For adiabatic throttling: $\Delta \hat{H}_m = \Delta \hat{H}_{out}$ hence you can read on chart:

- (a) $T \approx 130^\circ\text{F}$
- (b) Superheated conditions mean the quality = 100% vapor
- (c) Specific volume from chart = $2.5 \text{ ft}^3/\text{lb}$

Solutions Chapter 24



Point C is given. Point D is given. The quality at D is about 0.8.



24.25

Part a

Assume the process is a steady-state open process. The system is the turbine.

The energy balance is

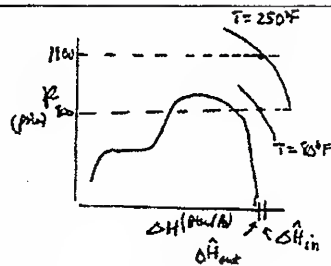
(continued)

$$\Delta E = Q + W - \Delta H - \Delta PE - \Delta KE$$

$$\Delta E = 0 \text{ (steady state)}$$

$$\Delta PE = 0$$

$$\Delta KE \approx 0 \text{ (quite small effect)}$$



so that the energy balance reduces to $Q + W = \Delta H$

$$\Delta \hat{H}_{in} = 177 \text{ Btu/lb} \quad \Delta \hat{H}_{out} = 135 \text{ Btu/lb} \quad Q = -25 \text{ Btu/lb}$$

Basis: 1 lb steam

$$\hat{W} = -(-25) + (135 - 177) = \boxed{-17 \text{ Btu/lb}} \text{ (Work done by turbine)}$$

Part b

The system is the valve. The energy balance is not needed because the CO_2 is saturated at 140 psia, hence this corresponds to $\boxed{38^\circ\text{F}}$.

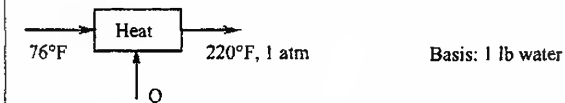
Part c

The energy balance reduces to

$$\hat{Q} = \Delta \hat{H} = \Delta \hat{H}_{out} - \Delta \hat{H}_{in} = 95 - 135 = \boxed{-40 \text{ Btu/lb}} \text{ (heat removed)}$$

24.26

Assume a steady-state open process. The system is the heater.



Basis: 1 lb water

Data:	p (psia)	$\hat{V}$ (ft ³ /lb)
76°F:	0.444	0.01607
220°F	14.696	27.15

Ignore the vapor that exists at the initial state. The water is superheated at the final condition.

$$\text{The energy balance reduces to: } Q = \Delta H = 1154.4 - 44.03 = \boxed{1110.4 \text{ Btu/lb}}$$

Alternate solution

Assume an unsteady state process with no mass exchanger between the system and surroundings.

The energy balance reduces to

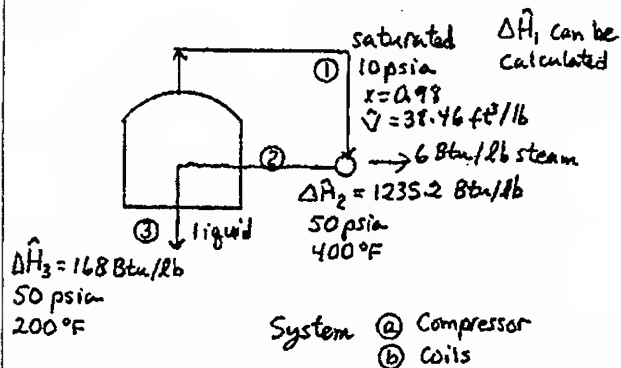
$$\Delta E = \Delta U = Q$$

Calculate

$$\begin{aligned} \Delta U &= \Delta H - \Delta(pV) = 1110.4 - \frac{144 \text{ in}^2}{\text{ft}^2} \left[\frac{(27.15)(14.696) - (0.01607)(0.444)(\text{ft}^3)(\text{lb}_f)}{(\text{lb})(\text{in.})^2} \right] \frac{1 \text{ Btu}}{778(\text{ft})(\text{lb}_f)} \\ &= 1110.4 - 73.9 = \boxed{1036.5 \text{ Btu/lb}} \end{aligned} \quad \text{(continued)}$$

or use the $\hat{U}$ values from the steam tables to avoid calculating $\Delta(pV)$.

24.27



To make the process a steady state open process from (1) to (3) assume the system is the coil plus the compressor. Then

$$\Delta \hat{E} = -\Delta[(\hat{H} + \hat{P} + \hat{K})m + Q + W] \quad \text{or} \quad W = \Delta H - Q$$

Basis: 1 lb water evaporated

Calculate $\Delta \hat{H}$ @ (1): $(0.98)(1143.3) + (0.02)(161.17) = 1123.6 \text{ Btu/lb}$

From (1) to (2): Balance on the compressor

$$\Delta \hat{H}_2 - \Delta \hat{H}_1 = 1235.2 - 1126.6 = 111.6 \text{ Btu/lb} \quad \hat{Q} = -6 \text{ Btu/lb}$$

$$W = 111.6 - (-6) = \boxed{117.6 \text{ Btu/lb}}$$

From (2) to (3): Balance on the coil

$$\Delta \hat{H}_3 - \Delta \hat{H}_2 = 168 - 1235.2 = -1067.2 \text{ Btu/lb} \quad \hat{W} = 0 \text{ so } \hat{Q} = \Delta \hat{H} = -1067.2 \text{ Btu/lb}$$

a. $\frac{\hat{Q}}{\hat{W}} = \frac{1067.2}{117.6} = \boxed{9.1}$ (Note: the problem asks for the heat transfer out as a + value)

$$V_1 = \left[\frac{38.46 \text{ ft}^3}{\text{lb}} \mid \frac{0.98}{\text{lb}} + \frac{(0.016) \text{ ft}^3}{\text{lb}} \mid \frac{0.02}{\text{lb}} \right] \frac{\text{lb steam}}{1067.2 \text{ Btu}} = 37.69 \text{ ft}^3/\text{lb}$$

Basis: 1,000,000 Btu/hr

b. $\frac{10^6 \text{ Btu}}{\text{hr}} \mid \frac{1 \text{ hr}}{60 \text{ min}} \mid \frac{1 \text{ lb steam}}{1067.2 \text{ Btu}} \mid \frac{37.69 \text{ ft}^3}{\text{lb steam}} = \boxed{589 \text{ ft}^3/\text{min}}$

24.28

Basis: 55 gallon oil, °API = 15

$$C_p = 0.41 \frac{\text{Btu}}{(\text{lb}) (^\circ\text{F})} @ 70^\circ\text{F}; \quad C_p = 0.467 \frac{\text{Btu}}{(\text{lb}) (^\circ\text{F})} @ 180^\circ\text{F}$$

$$C_{p_{\text{avg}}} = 0.5 (0.41 + 0.467) = 0.44 \text{ Btu/(lb)} (^\circ\text{F})$$

$$\text{sp. gr.} = \frac{141.5}{^\circ\text{API} + 131.5} = 0.966$$

$$\Delta H_{\text{oil}} = (0.44) (180 - 70) (55) (0.966) (8.33) = 21,500 \text{ Btu} \quad (\text{continued})$$

Solutions Chapter 24

Assume water leaves @ 212°F, saturated liquid:

$$\Delta \hat{H}_{H_2O} @ 212^\circ\text{F} = 180.07 \text{ Btu/lb}$$

$$\Delta \hat{H}_{H_2O} @ 220^\circ\text{F} = 1153.3 \text{ Btu/lb}$$

$$\text{Then } \Delta \hat{H}_{H_2O} = 1153.3 - 180 = 973 \text{ Btu/lb}$$

$$m_{\text{steam}} = \frac{21,500 \text{ Btu}}{973 \text{ Btu}} \times \frac{1 \text{ lb}}{1} = \boxed{22.1 \text{ lb stea}}$$

24.29

Process: Flow, steady-state

System: the pipeline

a. $Q + W = (\Delta H + \Delta KE + \Delta PE)$

Assume $\Delta \hat{KE}$

$$\dot{W} = 0$$

Basis: 1 lb_m of oil

$$\hat{Q} = \frac{1 \times 10^5 \text{ Btu}}{\text{hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{\text{min}}{2000 \text{ lb}} = 0.834 \text{ Btu/lb}_m$$

$$\Delta \hat{PE} = \frac{1000 \text{ ft}}{1} \times \frac{\text{g ft}}{\text{s}^2} \times \frac{(\text{lb}_f)(\text{s}^2)}{\text{g}_c (\text{lb}_m)(\text{ft})} \times \frac{1 \text{ Btu}}{778 (\text{ft})(\text{lb}_f)} = -1.285 \frac{\text{Btu}}{\text{lb}}$$

$$\text{Without the pump } \Delta H = Q - \Delta PE: \Delta \hat{H} = 0.834 - (-1.285) = \boxed{2.120 \text{ Btu/lb}}$$

Solutions Chapter 24

$$b. W = \frac{1 \text{ hp}}{1} \times \frac{0.50}{1} \times \frac{550 (\text{ft})(\text{lb}_f)}{(\text{sec})(\text{hp})} \times \frac{60 \text{ sec}}{\text{min}} \times \frac{1 \text{ Btu}}{778 (\text{ft})(\text{lb}_f)} \times \frac{\text{min}}{2000 \text{ lb}_m} = 0.0106 \text{ Btu/lb}$$

$$\Delta H = Q + W - \Delta PE$$

$$\text{With the pump: } \Delta H = 0.834 - (-1.285) + (0.0106) = \boxed{2.131 \text{ Btu/lb}}$$

24.30

$\dot{H}$ (Btu/lb)

①	→	②	satd. liquid	0.15	180.17
500°F			satd. vapor	0.85	1150.5
250 psia				1.00	
$\hat{H}_1 = 1264.7 \text{ Btu/lb}$				0.15 (180.17) + 0.85 (1150.5)	
					= 1005

Basis: 1 hour

Assume a steady state flow system ($\Delta E = 0$) $\Delta PE = \Delta KE = 0$. Then

$$\Delta H = Q + W$$

$$\Delta H = m(\Delta \hat{H}_2 - \Delta \hat{H}_1) = 1000 (1005 - 1264.7) = -259,700 \text{ Btu}$$

$$W = \frac{-86.5 \text{ hp}}{1} \times \frac{33,500 (\text{ft})(\text{lb}_f)}{(\text{hp})(\text{min})} \times \frac{1 \text{ Btu}}{778 (\text{ft})(\text{lb}_f)} \times \frac{60 \text{ min}}{\text{hr}} = -223,500 \text{ Btu/hour}$$

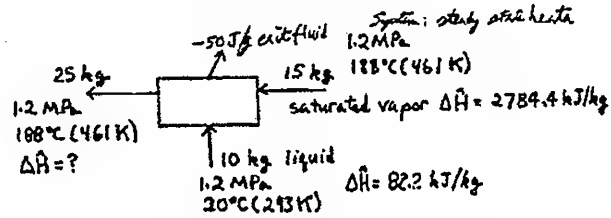
$$Q = \Delta H - W = -258,600 - (-223,500)$$

$$= \boxed{-36,400 \text{ Btu/hr}} \quad (\text{heat loss})$$

$$\text{The turbine does not operate adiabatically. The ratio } \left| \frac{Q}{\Delta H} \right| = \frac{36,400}{259,700} = \boxed{0.13}$$

24.31

Basis: 25 kg exit fluid



$$Q + W = \Delta H \quad W = 0$$

$$Q = \Delta H = \Delta H_{25} - \Delta H_{15} - \Delta H_{10} = \Delta H_{25} - (2784.4)(15) - (82.2)(10)$$

$$Q = \frac{-50 \text{ J/g} \times 25 \times 10^3 \text{ g}}{\text{g exit}} = -1250 \text{ kJ} \quad (\text{note } \Delta\hat{K}E \sim 10^{-4} \text{ J})$$

For the exit fluid

$$\begin{cases} \Delta\hat{H}_L = 798.5 \text{ kJ/kg} \\ \Delta\hat{H}_V = 2784.4 \text{ kJ/kg} \end{cases}$$

Let $x = \text{kg vapor}$, $25 - x = \text{kg liquid}$

$$-1250 = \frac{x \text{ kg} \times 2784.4 \text{ kJ}}{\text{kg}} + \frac{(25-x) \text{ kg} \times 798.5 \text{ kJ}}{\text{kg}} - \frac{15 \text{ kg} \times 2784.4 \text{ kJ}}{\text{kg}} - \frac{10 \text{ kg} \times 82.2 \text{ kJ}}{\text{kg}}$$

$$-1250 = 2784.4x + 19,963 - 798.5x - 41,766 - 822$$

$$x = 10.76 \quad \text{fraction vapor} = \frac{10.76}{25.0} = \boxed{0.43}$$

24.32

Open, unsteady state system (the tubing)

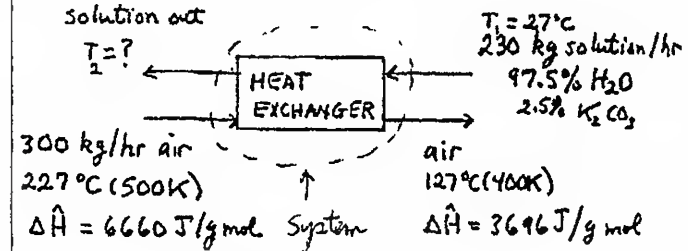
Basis: 1 hour

The energy balance reduces to $Q = \Delta H = mC_p\Delta T$.

$$Q = \frac{300 \text{ Btu}}{(\text{hr})(\text{ft})} \left| \frac{\text{L ft}}{(\text{hr})(\text{ft})} \right| \frac{1 \text{ hr}}{60 \text{ min}} = \frac{1 \text{ gal H}_2\text{O}}{\text{min}} \left| \frac{60 \text{ min}}{\text{hr}} \right| \frac{1 \text{ hr}}{0.1337 \text{ ft}^3} \left| \frac{1 \text{ lb H}_2\text{O}}{1 \text{ gal}} \right| \frac{1 \text{ Btu}}{0.0162 \text{ ft}^3} \left| \frac{(200-50)^\circ\text{F}}{(\text{lb})(^\circ\text{F})} \right|$$

$$\boxed{L = 248 \text{ ft}}$$

24.33



Basis: 1 hr

The energy balance reduces to

$$\Delta H = 0$$

$$\Delta H_{\text{air}} + \Delta H_{\text{soln}} = 0$$

(continued)

Solutions Chapter 24

For aqueous solutions, the heat capacity is dominated by the water, and the solute mass may be neglected with minimal error.

$$m(\Delta H_{\text{air}}^{400} - \Delta H_{\text{air}}^{500}) + m(\Delta H_{\text{H}_2\text{O}}^{T_2} - \Delta H_{\text{H}_2\text{O}}^{300}) = 0$$

$$\frac{1 \text{ hr} | 300 \text{ kg} | (3696 - 6660) \text{ J} | \text{g mol} | 1000 \text{ g} | \text{kg} | \text{kJ}}{\text{hr} | \text{g mol} | 29 \text{ g} | \text{kg} | 1000 \text{ J}}$$

$$+ \frac{1 \text{ hr} | 230 \text{ kg soln} | 97.5 \text{ kg H}_2\text{O} | (\Delta H_{\text{H}_2\text{O}}^{T_2} - 111.7) \text{ kJ}}{\text{hr} | 100 \text{ kg soln} | \text{kg}} = 0$$

$$\Delta H_{\text{H}_2\text{O}}^{T_2} = \frac{(30,622 + 25,049) \text{ kJ}}{224.25 \text{ kg}} = \boxed{248 \frac{\text{kJ}}{\text{kg}}}$$

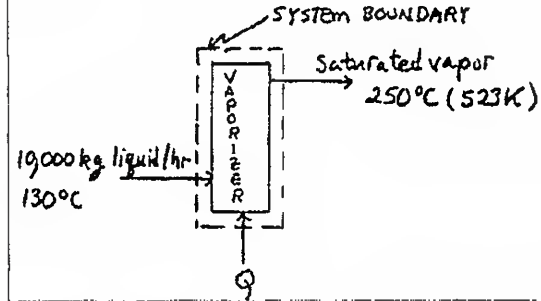
Interpolating from SI steam tables

$$330 \text{ K} + \frac{(335 - 330) \text{ K}}{(259.4 - 238.4) \frac{\text{kJ}}{\text{kg}}} (248.25 - 238.4) \frac{\text{kJ}}{\text{kg}}$$

$$= \boxed{332 \text{ K or } 59^\circ \text{C}}$$

Solutions Chapter 24

24.34



Basis: 1 hr

Open system, steady state

$$DH = Q + W$$

$$W = 0$$

$$Q = DH_{\text{liq}} + DH_{\text{vap}} \text{ at } 6 \text{ bp.}$$

$$= m \left[\int_{130}^{250} C_p dT + \Delta H_{\text{vap}} \text{ at } 250^\circ \text{C} \right]$$

Since the data are incomplete the following assumptions are made:

1. C_p is linear in T and the average value may be used.
2. The vapor behaves ideally.
3. V_L is negligible with respect to V_V .

(continued)

4. $\Delta \hat{H}_{\text{vap}}$ is constant within the temperature range of concern.

By 1, $C_{pL} = \frac{(2.09 + 2.13) \text{ J/(g)} (^\circ\text{C})}{2} = 2.11 \text{ J/(g)} (^\circ\text{C})$

By 2, 3, 4 the Clausius Clapeyron equation reduces to

$$\log_{10} \frac{p^*_1}{p^*_2} = \frac{\Delta \hat{H}_{\text{vap}}}{2.303 R} \left(\frac{1}{T_2} - \frac{1}{T_1} \right)$$

Substituting values:

$$\log_{10} \left(\frac{55.0 \text{ kPa}}{101.3 \text{ kPa}} \right) = \frac{\Delta \hat{H}_{\text{vap}}}{2.303} \left(\frac{\text{g mol}}{8.314 \text{ J}} \right) \left(\frac{\text{K}}{523 \text{ K}} - \frac{1}{503 \text{ K}} \right)$$

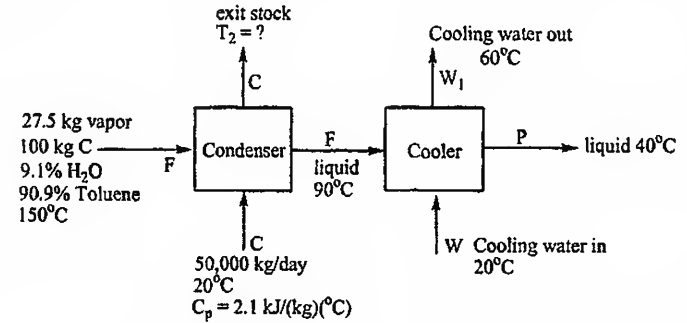
$$-0.2654 = -3.97060 \times 10^{-6} \Delta \hat{H}_{\text{vap}} \frac{\text{g mol}}{\text{J}}$$

$$\Delta \hat{H}_{\text{vap}} = \frac{-0.2654 \text{ J}}{-3.9706 \times 10^{-6} \text{ g mol}} \left| \frac{1 \text{ g mol}}{122 \text{ g}} \right| = 547.88 \text{ kJ/kg}$$

$$Q = \frac{1 \text{ hr}}{1} \left| \frac{10,000 \text{ kg}}{\text{hr}} \left(\frac{2.11 \text{ kJ}}{(\text{kg}) (^\circ\text{C})} \right) (250 - 130) ^\circ\text{C} + \frac{547.88 \text{ kJ}}{\text{kg}} \right|$$

$$= 8,011,000 \text{ kJ}$$

24.35



Basis: 1 day

$$\frac{27.5 \text{ kg F}}{100.0 \text{ kg C}} \left| \frac{50,000 \text{ kg C}}{\text{day}} \right| \frac{1 \text{ day}}{1} = 13,750 \text{ kg F}$$

$$\frac{13,750 \text{ kg F}}{100 \text{ kg F}} \left| \frac{9.1 \text{ kg H}_2\text{O}}{100 \text{ kg F}} \right| = 1,251.25 \text{ kg H}_2\text{O}$$

$$13,750 \text{ kg F} - 1,251.25 \text{ kg H}_2\text{O} = 12,498.75 \text{ kg toluene.}$$

Energy balance at condenser:

The energy balance reduces to $\Delta H = 0$

$$\Delta H_C + \Delta H_F = 0$$

(continued)

Solutions Chapter 24

$$m_C \int_{20}^{T_2} C_p dT + m_{H_2O} \left[\int_{150}^{100} C_p dT - \Delta H_{\text{vap at } 100^\circ\text{C}} + \int_{100}^{90} C_p dT \right]$$

$$+ m_{\text{tol}} \left[\int_{150}^{111} C_p dT - \Delta H_{\text{vap at } 111^\circ\text{C}} + \int_{111}^{90} C_p dT \right] = 0$$

$$\frac{50,000 \text{ kg}}{1} \left| \frac{2.1 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right| \frac{T_2 - 20^\circ\text{C}}{1}$$

$$+ 1,251.25 \text{ kg H}_2\text{O} \left[\frac{2.1 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right] \frac{(100 - 150)^\circ\text{C}}{1} - \frac{2260 \text{ kJ}}{\text{kg}} + \frac{4.2 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \frac{(90 - 100)^\circ\text{C}}{1}$$

$$+ 12,498.75 \text{ kg tol} \left[\frac{1.3 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right] \frac{(111 - 150)^\circ\text{C}}{1} - \frac{230 \text{ kJ}}{\text{kg}} + \frac{1.7 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \frac{(90 - 111)^\circ\text{C}}{1} = 0$$

$$105,000 T_2 - 2,100,000 - 3,011,758.75 - 3,954,604.5 = 0$$

$$(a) \quad T_2 = \frac{9,066,363.25}{105,000} = \boxed{86.3^\circ\text{C}}$$

Enthalpy balance at cooler:

$$\Delta H = 0$$

$$(\Delta H_w^{\text{out}} - \Delta H_w^{\text{in}}) - (\Delta H_p - \Delta H_f) = 0$$

$$m_w \int_{20}^{60} C_p dT - \left[m_{H_2O} \int_{86.34}^{40} C_p dT - m_{td} \int_{86.34}^{40} C_p dT \right] = 0$$

$$\frac{m_w}{1} \left| \frac{4.2 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right| \frac{(60 - 20)^\circ\text{C}}{1} = \frac{1,251.25 \text{ kg H}_2\text{O}}{1} \left| \frac{4.2 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right| \frac{(40 - 90)^\circ\text{C}}{1}$$

Solutions Chapter 24

$$+ \frac{12498.75 \text{ kg tol}}{1} \left| \frac{1.7 \text{ kJ}}{(\text{kg})(^\circ\text{C})} \right| \frac{(40 - 90)^\circ\text{C}}{1}$$

$$m_w = 168 \frac{\text{kJ}}{\text{kg}} - 262,762 \text{ kJ} - 1,062,394 \text{ kJ}$$

$$m_w = \frac{1,325,156 \text{ kJ}}{168 \text{ kJ/kg}} = \boxed{7,887 \text{ kg H}_2\text{O}}$$

24.36

Basis: 1 lb water/steam

Steady-state, open system for each unit

The data:

Tabulation of p, T, $\hat{V}$, $\hat{H}$ and quality or superheats at the numbered points:

	1	2	3	4	5	6
p (psia)	14.7	250	250	250	40	0.306
T (°F)	65	65	401	550	268	65
$\hat{V}$ (ft ³ /lb)	0.026	0.016	1.844	2.202	10.14	0.016
qual./sup.heat	0%	0%	100%	149°	96.5%	0%
$\hat{H}$ (Btu/lb)	33.09	33.79	1201.1	1291	1137	33.05

Calculate the specific volume at point 5:

$$\hat{V} = 0.965(10.506) + 0.035(0.01715) = 10.14$$

(a) Heat to boiler:

$$Q = \Delta H = H_3 - H_2 = 1201.1 - 33.8 = 1167.3 \text{ Btu/lb}$$

(b) Heat to superheater:

(continued)

Solutions Chapter 24

$$Q = \Delta H = H_4 - H_1 = 1291 - 1201.1 = 90 \text{ Btu/lb}$$

(c) Heat removed in condenser = $H_6 - H_5 = 33 - 1137 = -1104 \text{ Btu/lb}$

(d) Work delivered by turbine: $Q + W = \Delta H$

$$Q = 0 \quad W = \Delta H = H_5 - H_4 = 1137 - 1291 = -154 \text{ Btu/lb}$$

(e) Work required by the pump between 1 and 2:

$$Q + W = \Delta H \quad Q = 0 \quad \text{hence } W = \Delta H$$

Because we do not have values of ΔH for compressed water at 65°F, we will use

$$W = \Delta U + \Delta(pV)$$

$$\Delta U = \int_{65^\circ\text{F}}^{65^\circ\text{F}} C_v dT = 0$$

$$\Delta(pV) = p_2 V_2 - p_1 V_1 = (p_2 - p_1) V = \frac{(250 - 14.7) \times 0.016 \times 144}{778} = 0.70 \text{ Btu/lb}$$

$$\text{Efficiency} = \frac{\text{Net work delivered}}{\text{Total heat Supplied}} = \frac{154 - 0.70}{1167.3 + 90}$$

$$= 0.121$$

For a water rate of 2000 lb/hr:

$$\text{hp} = \frac{154 \text{ Btu}}{\text{lb}} \times \frac{2000 \text{ lb steam}}{\text{hr}} \times \frac{1 \text{ hr}}{3600 \text{ s}} \times \frac{1.415 \text{ hp}}{1 \text{ Btu/s}} = 121$$

You can improve the efficiency by:

- Exhausting the turbine at a lower pressure.
- Use higher boiler pressure.
- Use higher superheat.

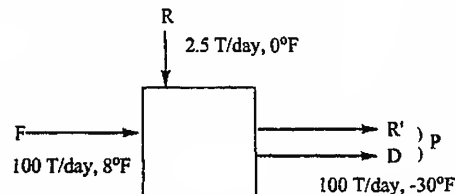
Solutions Chapter 24

24.37

Basis: 100 lb/day liquid Cl_2 feed at 8°F

Assume

- Adiabatic operation of all units
- Flow process, steady-state



First find the enthalpy lost or gained by the Cl_2 in the heat exchanger from which we can get the work done by compressor A on the Freon.

Overall Cl_2 balance through the heat exchanger

$$F + R = P \\ 100 + 2.5 = 102.5$$

Energy balance for Cl_2 through the heat exchanger

$$\begin{aligned} \text{For a flow process: } Q + W &= \Delta H \\ W &= 0 \\ Q &= \Delta H \end{aligned}$$

Choose as the reference state liquid Cl_2 at -30°F

(continued)

Solutions Chapter 24

$$\Delta H = H_{\text{out}} - H_{\text{in}} - H_{R_c}$$

$$= \frac{8.1 \text{ Btu}}{(\text{lb mol})(^\circ\text{F})} \left| \frac{\text{lb mol}}{71 \text{ lb}} \right| \left| \frac{102.5 \text{ lb}}{100 \text{ lb F}} \right| [-30 - (-30)^\circ\text{F}]$$

$$- \frac{8.1 \text{ Btu}}{(\text{lb mol})(^\circ\text{F})} \left| \frac{\text{lb mol}}{71 \text{ lb}} \right| \left| \frac{100 \text{ lb}}{100 \text{ lb F}} \right| [8 - (-30)^\circ\text{F}]$$

$$- \frac{8.1 \text{ Btu}}{(\text{lb mol})(^\circ\text{F})} \left| \frac{\text{lb mol}}{71 \text{ lb}} \right| \left| \frac{2.5 \text{ lb}}{100 \text{ lb F}} \right| [0 - (-30)^\circ\text{F}] = 0 - 433.5 - 8.55 = -442.1 \frac{\text{Btu}}{100 \text{ lb F}}$$

Consequently

$$Q = -442.1 \text{ Btu} / 100 \text{ lb F}$$

This means heat is lost by the Cl_2 and gained by the Freon

Energy balance for the Freon flowing through compressor A:

$$Q + W = \Delta H$$

But since the flow of Freon is cyclical

$$\Delta H = 0$$

$$Q_{\text{Freon}} = -Q_{\text{Cl}_2} = -(-442.1) = 442.1 \text{ Btu} / 100 \text{ lb F}$$

$$W_A = Q_{\text{Freon}} = 442.1 \frac{\text{Btu}}{100 \text{ lb F}}$$

Energy balance for the Cl_2 flowing through the compressor B:

$$2.5 \text{ lb/day @ } -30^\circ\text{F} \rightarrow 2.5 \text{ lb/day at } 0^\circ\text{F}$$

$$Q + W = \Delta H \quad Q = 0$$

Solutions Chapter 24

$$\Delta H = \text{Enthalpy change across compressor} = H_R - H_R'$$

Other units

$$W = 539 \text{ Btu/mole}$$

$$= 1,520,000 \text{ Btu/day}$$

$$H_R = C_p \Delta T + \Delta H_{\text{vap}}$$

$$\Delta H = \frac{2.5 \text{ lb}}{100 \text{ lb F}} \left| \frac{8.1}{71} \right| [0 - (-30)]$$

$$+ \frac{4878 \text{ cal}}{\text{g mol}} \left| \frac{1.8 \text{ Btu/lb}}{\text{cal/g mol}} \right| \left| \frac{1 \text{ lb mol}}{71 \text{ lb}} \right| \left| \frac{2.5 \text{ lb}}{100 \text{ lb F}} \right|$$

$$= 8.55 + 309 = 317.5 \frac{\text{Btu}}{100 \text{ lb F}}$$

Total work input needed to make the process operational:

$$\text{hp} = \frac{317.5 + 442.1 \text{ Btu}}{100 \text{ lb F}} \left| \frac{2000 \text{ lb}}{\text{ton}} \right| \left| \frac{100 \text{ ton F}}{\text{day}} \right| \left| \frac{778(\text{ft})(\text{lb}_f)}{\text{Btu}} \right|$$

$$\frac{1 \text{ day}}{(24) \times (60) \text{ min}} \left| \frac{(\text{hp})(\text{min})}{33,000(\text{ft})(\text{lb}_f)} \right| 0.30$$

$$= \boxed{82.9 \text{ horsepower}} \quad (\text{actual power input})$$

24.38

Basis: 1 day; Reference temp = 80°F

a. Material and Energy Balances:

Overall Material:

(continued)

Solutions Chapter 24

In = 1,000,000 lb
 Out : residue: 500,000 lb
 naptha: 200,000 lb
 gasoline: 300,000 lb
 Total out 1,000,000 lb

Tower 1:

Material	In		Out
feed	1,000,000	vapor	2,000,000
reflux	<u>1,500,000</u>	residue	<u>500,000</u>
total	2,500,000	total	2,500,000

Energy:

In: feed: $(1 \times 10^6)(0.53)(480 - 90) + 10^6(100)$
 $+ (10^6)(0.45)(500 - 480) =$ 315,000,000 Btu
 reflux: $(1.5 \times 10^6)(0.59)(180 - 90) =$ 79,700,000 Btu
 steam: (by difference) 114,500,000 Btu
 total: 509,700,000 Btu

Out: residue: $(5 \times 10^5)(0.51)(480 - 90) =$ 99,200,000
 vapor: $(2 \times 10^6)(111) =$ 222,000,000
 liquid: $(2 \times 10^6)(0.59)(250 - 90) =$ 188,500,000
 total (Btu): = 509,700,000

Furnace:

Material	In		Out
	1,000,000 lb		1,000,000 lb

Energy

	In		Out
feed:	$(10^6)(0.53)(200 - 90) =$ 58,300,000		
furnace ht:	<u>257,200,000</u>		
total: (Btu)	315,500,000		315,500,000

Condenser I:

Material

Solutions Chapter 24

In: vapor = 2.0×10^6 lb
 $H_2O: 304,500,000/(1)(120 - 70) =$ 6.1×10^6 lb
 Out: liquid: 2.0×10^6 lb

Energy

H_2O = 6.1×10^6 lb
 In: vapor: $222 \times 10^6 + 188.5 \times 10^6 =$ 410.5×10^6 Btu
 Out: liquid: $(2 \times 10^6)(0.59)(180 - 90) =$ 106×10^6 Btu
 Removed by water = 304.5×10^6 Btu
 Total out: = 410.5×10^6 Btu

Preheater I:

Material

In: liquid = 500×10^6 lb; Out: vapor = 500×10^6 lb

Energy

In: liquid: $(5 \times 10^5)(0.59)(180 - 90) =$ 26.5×10^6 Btu
 steam: = 78.65×10^6 Btu
 Total = 105.15×10^6 Btu
 Out: vapor: $(5 \times 10^5)(0.59)(250 - 90)$
 $+ (5 \times 10^5)(111)$
 $+ (5 \times 10^5)(0.51)(200 - 250) =$ 105.15×10^6 Btu

Tower II

Material

In: feed	= 500,000 lb	Out: vapor	= 900,000
reflux	= 600,000 lb	residue	= <u>200,000</u>
Total	= 1,100,000 lb	total	= 1,100,000

Energy

In: feed: = 105,150,000
 reflux: $(6 \times 10^5)(0.63)(120 - 90) =$ 11,300,000
 steam: (by difference) = 42,700,000
 Total: (Btu): = 159,150,000

(continued)

Solutions Chapter 24

$$\begin{aligned}\text{Out: vapor: } (9 \times 10^5)(0.63)(150-90) + 9 \times 10^5(118) &= 140.05 \times 10^6 \\ \text{residue: } (2 \times 10^5)(0.58)(255-90) &= 19.1 \times 10^6 \\ \text{Total (Btu):} &= 159.15 \times 10^6\end{aligned}$$

Condenser II

Material

$$\begin{aligned}\text{In: vapor:} &= 0.9 \times 10^6 \text{ lb} \\ \text{H}_2\text{O: } \frac{123.05 \times 10^6}{(1)(110-70)} &= 3.08 \times 10^6 \text{ lb}\end{aligned}$$

$$\begin{aligned}\text{Out: liquid} &= 0.9 \times 10^6 \text{ lb} \\ \text{H}_2\text{O} &= 3.08 \times 10^6 \text{ lb}\end{aligned}$$

Energy

$$\begin{aligned}\text{In: (Btu)} &= 140.05 \times 10^6 \\ \text{Out: liquid: } (9 \times 10^5)(0.63)(120-90) &= 17 \times 10^6 \\ \text{removed by H}_2\text{O:} &= 123.05 \times 10^6 \\ \text{Total (Btu):} &= 140.05 \times 10^6\end{aligned}$$

Heat Exchanger II (Assume $T_{\text{out}} = 90^\circ\text{F}$)

Material	In		Out
liquid:	300,000 lb	liquid:	300,000
H ₂ O: $5,670,000/(1)(80-70) =$	567,000 lb	H ₂ O:	567,000

Energy

$$\begin{aligned}\text{In: } (300,000)(0.63)(120-90) &= 5.67 \times 10^6 \text{ Btu} \\ \text{Out: liquid:} &= 0.00 \\ \text{removed by H}_2\text{O} &= 5.67 \times 10^6 \text{ Btu}\end{aligned}$$

Heat Exchanger III

Material

Solutions Chapter 24

$$\begin{aligned}\text{In = Out:} \\ \text{Bottoms} &200,000 \text{ lb} \\ \text{Charge} &1,000,000 \text{ lb}\end{aligned}$$

Energy

$$\begin{aligned}\text{In: } (200,000)(0.58)(255-90) &= 19.15 \times 10^6 \\ (1 \times 10^6)(0.53)(90-90) &= 0.0 \\ \text{Total (Btu):} &= 19.15 \times 10^6 \\ \text{Out: } (2 \times 10^5)(0.58)(26.3-90) &= -7.35 \times 10^6 \\ (1 \times 10^6)(0.53)(140-90) &= 26.5 \times 10^6 \\ \text{Total (Btu):} &= 19.15 \times 10^6\end{aligned}$$

T_{out} of 26.3°F does not seem reasonable

Heat Exchanger IV

Material

$$\begin{aligned}\text{In = Out} \\ \text{Bottoms} &0.5 \times 10^6 \text{ lb} \\ \text{Charge} &1.0 \times 10^6 \text{ lb}\end{aligned}$$

Energy

$$\begin{aligned}\text{In: } (5 \times 10^5)(0.51)(480-90) &= 99.3 \times 10^6 \\ (1 \times 10^6)(0.53)(140-90) &= 26.5 \times 10^6 \\ \text{Total (Btu):} &= 125.8 \times 10^6 \\ \text{Out: } (5 \times 10^5)(0.51)(257-90) &= 67.5 \times 10^6 \\ (1 \times 10^6)(0.53)(200-90) &= 58.3 \times 10^6 \\ \text{Total (Btu):} &= 125.8 \times 10^6\end{aligned}$$

$$\text{Heat load of furnace} = 315.5 \times 10^6 - 58.3 \times 10^6 = \boxed{257.2 \times 10^6 \text{ Btu}}$$

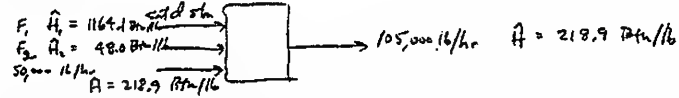
b. Additional heat if charge to furnace is at 90°F

$$\text{Total heat load} = 315.5 \times 10^6 \text{ Btu}$$

$$\text{Additional heat} = 315.5 \times 10^6 - 257.2 \times 10^6 = \boxed{58.3 \times 10^6 \text{ Btu}}$$

24.39

Basis: 1 hour Open steady-state process

Deaerator BalanceMaterial Balance

$$F_1 + F_2 + 50,000 = 105,000$$

$$F_2 = 105,000 - 50,000 - F_1$$

Energy Balance

$$F_1(1164.1) + F_2(48.0) + 50,000(218.9) = 105,000(218.9)$$

$$F_1(1164.1) + (55,000 - F_1)(48.0) = 55,000(218.9)$$

a. $F_2 = \boxed{8,422 \text{ lb/hr}}$ steam

b. $F_2 = \boxed{46,578 \text{ lb/hr}}$ make-up feedwater

Boiler Feedwater Pump

$$\dot{m} \hat{V} \Delta p = \left(105,000 \frac{\text{lb}}{\text{hr}} \right) \left(0.017 \frac{\text{ft}}{\text{lb}} \right) \left(800 - 30 \frac{\text{lb}_f}{\text{in}^2} \right) \left(\frac{144 \text{ in}^2}{\text{ft}^2} \right) \left(\frac{(\text{hp})(\text{s})}{550(\text{ft})(\text{lb}_f)} \right) \left(\frac{\text{hr}}{3600\text{s}} \right)$$

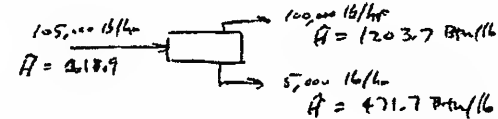
$$= 100 \text{ hp}$$

c. For 55% efficiency: $\boxed{181.7 \text{ hp}}$

d. $(181.7 \text{ hp}) \left(0.7457 \frac{\text{kW}}{\text{hp}} \right) = \boxed{135.5 \text{ kW}}$

e. $(135.5 \text{ kW}) \left(8760 \frac{\text{hr}}{\text{yr}} \right) (\$0.05 / \text{kWhr}) = \boxed{\$59,360 / \text{year}}$

f. Savings = $(105,000)(0.017)(200)(144) \left(\frac{1}{550} \right) \left(\frac{1}{3600} \right) \left(\frac{0.7457}{0.55} \right) (8760)((0.05))$
 $= \boxed{\$15,420 / \text{year}}$

Steam Drum

$$(100,000)(1230.7) + (5000)(471.7) - 105,000(218.9) = 102.4 \times 10^6 \text{ Btu/hr}$$

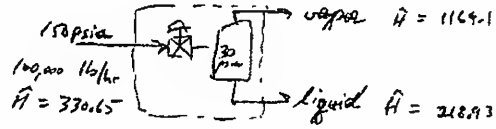
g. Steam Drum Heat Input = $\boxed{102.4 \times 10^6 \text{ Btu/hr}}$

h. Superheater = $(100,000)(1351.8 - 1230.7) = \boxed{12.1 \times 10^6 \text{ Btu/hr}}$

Flash Drum

(continued)

Solutions Chapter 24



x = vapor flowrate

$$(100,000 - x)(218.93) + x(1164.1) = 100,000(330.65)$$

$x = 11,820 \text{ lb/hr} = \text{vapor flowrate}$

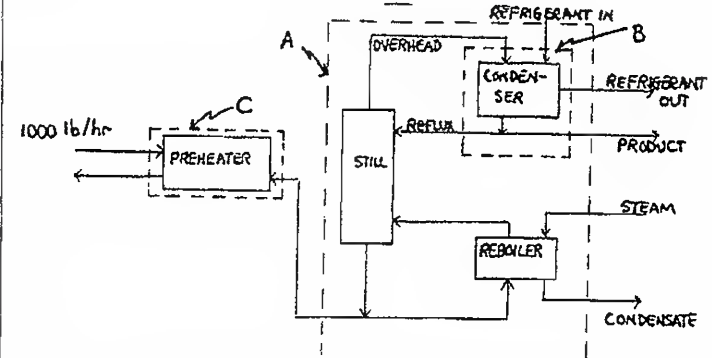
and $88,180 \text{ lb/hr} = \text{liquid flowrate}$

i. Steam Lost $= 11,820 - 8,422 = \boxed{3,398 \text{ lb/hr}}$

j. Condensate Lost $= 88,180 - 50,000 = \boxed{38,180 \text{ lb/hr}}$

Solutions Chapter 24

24.40



Basis: one hour operation open, steady-state process.

A material balance initially is necessary to determine amounts and compositions of streams.

A. Feed

Component	Wt. %	lb
C_2H_6	65	650
C_2H_4	35	350

B. Product

Have 97% recovery of ethylene

$$\text{lb } C_2H_4 = (0.97)(350) = 340$$

(continued)

Now, since the product is 98% C_2H_4

$$\frac{340 \text{ lb } C_2H_4}{98 \text{ lb } C_2H_4} \left| \frac{2 \text{ lb } C_2H_6}{98 \text{ lb } C_2H_4} \right. = 6.95 \text{ lb } C_2H_6$$

Component	Wt. %	lb
C_2H_6	2	6.95
C_2H_4	98	340

C. Bottoms

$$\begin{aligned} \text{lb } C_2H_4 &= 350 - 340 = 10 \\ \text{lb } C_2H_6 &= 650 - 6.95 = 643.05 \end{aligned}$$

Component	Wt. %	lb
C_2H_6	98.47	643.05
C_2H_4	1.53	10

We are now ready to determine, by a series of energy balances, the quantities desired.

Energy Balance on System "A" (see Fig.)

$$\text{Energy in with Feed} + \text{energy in with steam} = \begin{cases} \text{Energy out with Product} + \\ \text{Energy out with bottoms} + \\ \text{Energy out with refrigerant} \end{cases}$$

We will assign an arbitrary enthalpy of zero to the liquid feed as it enters the Pre-heater at -100°F . Actually, any reference condition could be chosen since we are only concerned with enthalpy changes in the balances.

The feed undergoes a 20°F rise before it enters the still.

$T = -80^\circ\text{F}$ and

$$C_p \text{ feed} = (0.65) (0.65) + (0.35) (0.55) = 0.62 \text{ Btu/(lb)} (^\circ\text{F})$$

$$\begin{aligned} \text{Enthalpy in with feed} &= (\text{lb feed}) (C_p \Delta T) = (1000) (0.62) (-80 - (-100)) \\ &= 12,400 \text{ Btu/hr} \end{aligned}$$

Enthalpy in with steam = (lb steam) (ΔH_v) at 30 psig,

$$\Delta H_v = 945 \text{ Btu/lb}$$

$$\text{Enthalpy in with steam} = (S) (945) \text{ Btu/hr}$$

From the data given, the temperature of the saturated liquid product is 30°F since it is essentially pure ethylene.

$$C_p = 0.55 \text{ Btu/(lb)} (^\circ\text{F})$$

$$\text{Enthalpy out with product} = (346.95) (0.55) [-30 - (-100)] = 13,360 \text{ Btu/hr}$$

The bottoms are practically pure ethane so, $T = 10^\circ\text{F}$,

$$C_p = 0.65 \text{ Btu/(lb)} (^\circ\text{F})$$

$$\text{Enthalpy out with bottoms} = (653.05) (0.65) [10 - (-100)] = 46,700 \text{ Btu/hr}$$

The refrigerant experiences a temperature rise of 25°F as it passes through the condenser. The heat capacity may be assumed to be $1.0 \text{ Btu/(lb)} (^\circ\text{F})$

$$\text{Enthalpy out with refrigerant} = (\text{lb refig.}) (1.0) (25) \text{ Btu/hr}$$

Now, rewriting the energy balance "A" with a substitution of known terms:

$$12,400 + 945S = 13,360 + 46,700 + 25m \quad (1)$$

(continued)

Solutions Chapter 24

It is evident from this first balance that a second balance will be necessary to determine the unknown quantities.

Energy Balance "B"

$$\text{Energy in with Overhead} = \begin{array}{l} \text{Energy out with refrigerant +} \\ \text{Energy out with Product +} \\ \text{Energy out with Reflux} \end{array}$$

Since we are using a reflux ration of 6.1

$$\text{lb reflux} = (6.1) (346.95) = 2,120 \text{ lb/hr.}$$

Now, the specific enthalpy of the reflux = the specific enthalpy of the product, since they are from the same stream, and the differences in enthalpy between the overhead and the product, or overhead and reflux, is merely the heat of vaporization of ethylene (neglecting the small amount of C_2H_6 present), therefore, we can rewrite Energy Balance "B" as:

$$(\text{lb Overhead}) (\Delta H_v) = 25 \text{ m}$$

$$(2,120 + 346.95) (135) = 25 \text{ m}$$

$$\text{or } m = 13,320 \text{ lb/hr.}$$

Now substituting this value into equation (1) we have

$$12,400 + 945 S = 13,360 + 46,700 + (25) (13,320)$$

$$\text{so that } \boxed{S = 403 \text{ lb/hr}}$$

$$\text{a. } \frac{403 \text{ lb steam}}{\text{hr}} \left| \frac{\text{hr}}{1000 \text{ lb feed}} \right| = 0.403 \text{ lb steam/lb feed}$$

$$\text{b. } \frac{13,320 \text{ lb refrigerant}}{\text{hr}} \left| \frac{1 \text{ ft}^3 \text{ refig.}}{50 \text{ lb refig.}} \right| \left| \frac{7.48 \text{ gallons}}{\text{ft}^3} \right| = \boxed{1,993 \text{ gallons of refrigerant/hr}}$$

Solutions Chapter 24

The bottoms leave the still and enter the Pre-heater at approximately 10°F , the saturation temperature of pure C_2H_6 . The final temperature of the bottoms as it leaves the Pre-heater can be calculated from a simple energy balance around the Pre-heater.

c. Enthalpy Balance "C"

$$(\text{lb bottoms}) [0.65 \text{ Btu/(lb)} (^\circ\text{F})] (10 - T_f) = (\text{lb feed})$$

$$\times [0.62 \text{ Btu/(lb)} (^\circ\text{F})] [-80 - (-100)]$$

$$(653.05) (0.54) (10 - T_f) = (1000) (0.62) (20)$$

$$\boxed{T_f = 19.2^\circ\text{F}}$$

25.1

(2), (4), (6)

25.2

(1)

25.3

(3)

25.4

	$\Delta H^\circ (\text{kJ})$
$\text{C}_3\text{H}_8(\text{g}) \rightarrow \text{C}_3\text{H}_6(\text{g}) + \text{H}_2(\text{g})$	+123.8
$3\text{CO}_2(\text{g}) + 4\text{H}_2\text{O}(\text{l}) \rightarrow \text{C}_3\text{H}_8(\text{g}) + 5\text{O}_2(\text{g})$	+2220.0
$4[\text{H}_2(\text{g}) + 1/2\text{O}_2(\text{g}) \rightarrow \text{H}_2\text{O}(\text{l})]$	$4 \times (-285.8)$
$3[\text{C}(\text{s}) + \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g})]$	$3 \times (-393.4)$



$$\Delta H^\circ_f \text{ of } \text{C}_3\text{H}_6 = \boxed{20.1 \text{ kJ/g mol}}$$

25.5

The ΔH°_f is 0 by definition.

25.6

Basis: 1 g mol C_3H_2

	$\Delta H (\text{kJ/g mol})$
$5 \text{CO}_2(\text{g}) + \text{H}_2\text{O}(\ell) \rightarrow \text{C}_3\text{H}_2(\text{s}) + 5\frac{1}{2}\text{O}_2(\text{g})$	2110.5
add: $5[\text{C}(\text{s}) + \text{O}_2(\text{g})] \rightarrow 5[\text{CO}_2(\text{g})]$	$5[-394.1]$
add: $\text{H}_2(\text{g}) + \frac{1}{2}\text{O}_2(\text{g}) \rightarrow \text{H}_2\text{O}(\text{g})$	-241.826
add: $\text{H}_2\text{O}(\text{g}) \rightarrow \text{H}_2\text{O}(\ell)$	<u>-43.911</u>
net: $5\text{C}(\text{s}) + \text{H}_2(\text{g}) \rightarrow \text{C}_3\text{H}_2(\text{s})$	$\Delta H^\circ_f = \boxed{-143.737 \text{ kJ/g mol}}$

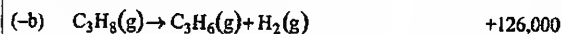
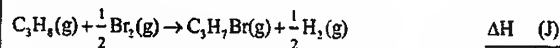
25.7

- (a) $\text{NH}_4(\ell)$: -67.20 kJ/g mol from Appendix F
 (b) Formaldehyde gas (H_2CO): -115.89 kJ/g mol from Appendix F
 (c) Acetaldehyde liquid (CH_3CHO):

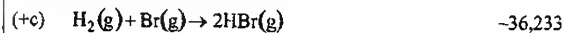
For gas $\Delta H^\circ_f = -166.4 \text{ kJ/g mol}$ from Appendix FThe heat of vaporization at 293.2 K is 25.732 kJ/g mol from the CD. The value is close enough to ΔH_{vap} (298 K) to use.

$$\Delta H^\circ_f = -166.4 + 25.732 = -140.7 \text{ kJ/g mol}$$

25.8

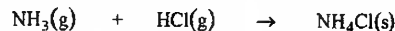
You want to get ΔH for

(continued)



$$\text{Total} \quad \boxed{-10,029} \text{ J / g mol C}_3\text{H}_8$$

25.9

a. Basis: 1 g mol $\text{NH}_3(\text{g})$ 

$$\Delta \hat{H}_f^\circ (\text{kJ / g mol}): \quad -46.191 \quad -92.311 \quad -315.4$$

$$\Delta H_{\text{rxn}}^\circ = \sum n_i \Delta \hat{H}_i^\circ - \sum n_i \Delta \hat{H}_i^\circ$$

$$= (1)(-315.4) - [(1)(-46.191) + (1)(-92.311)]$$

$$= \boxed{-176.9 \text{ kJ / g mol NH}_3(\text{g})}$$

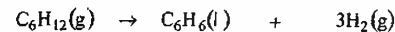
b. Basis: 1 g mol $\text{CH}_4(\text{g})$ 

$$\Delta \hat{H}_f^\circ (\text{kJ / g mol}): \quad -74.84 \quad 0 \quad -393.51 \quad -285.840$$

$$\Delta H_{\text{rxn}}^\circ = \sum n_i \Delta \hat{H}_i^\circ - \sum n_i \Delta \hat{H}_i^\circ$$

$$= [(2)(-285.840) + (1)(-393.51)] - [(1)(-74.84) + 0]$$

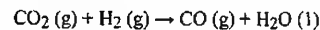
$$= -890.4 \text{ kJ / g mol CH}_4(\text{g})$$

c. Basis: 1 g mol $\text{C}_6\text{H}_2(\text{g})$ 

$$\Delta \hat{H}_f^\circ (\text{kJ / g mol}): \quad -123.1 \quad +48.66 \quad 0$$

$$\Delta H_{\text{rxn}}^\circ = [0 + (1)(+48.66)] - [(1)(-123.1)] = \boxed{171.76 \text{ kJ / g mol C}_6\text{H}_{12}(\text{g})}$$

25.10

a. Basis: 1 g mol $\text{CO}_2(\text{g})$ 

$$\Delta H_{\text{rxn}}^\circ = (-110.52 - 285.84) - (-393.51) = \boxed{-2,849 \text{ kJ}}$$

b. Basis: 1 g mol CaO(s)

$$\Delta H_{\text{rxn}}^\circ = (-986.59 - 924.66) - [(-635.55 - 601.83) - 2(285.84)] =$$

$$\boxed{-102,19 \text{ kJ per mol CaO(s)}}$$

$$\text{Multiply by 2 for the reaction listed} \quad \boxed{-204,38 \text{ kJ}}$$

c. Basis: 1 g mol $\text{Na}_2\text{SO}_4(\text{s})$

$$\Delta H_{\text{rxn}}^\circ = (-1090.35 - 110.54) - (-1384.49) = \boxed{183,59 \text{ kJ}}$$

(continued)

d. Basis: 1 g mol NaCl (s)

$$\Delta H^\circ_{\text{rxn}} = (-92.31 - 1126.33) - (-811.32 - 411.01) = \boxed{3.67 \text{ kJ}}$$

e. Basis: 1 g mol O₂

$$\Delta H^\circ_{\text{rxn}} = [2(-1384.5) + 4(-92.31)] - [(-411.00) + 2(-296.90) + 2(-285.84)] = \boxed{-1561.76}$$

f. Basis: 1 g mol SO₂ (g)

$$\Delta H^\circ_{\text{rxn}} = (-811.32) - (-285.84 - 296.90) = \boxed{-228.58 \text{ kJ}}$$

g. Basis: 1 g mol N₂

$$\Delta H^\circ_{\text{rxn}} = 2(90.374) = \boxed{180.75 \text{ kJ}}$$

h. Basis: 1 g mol Na₂CO₃ (s)

$$\Delta H^\circ_{\text{rxn}} = [3(-1117.13) + (-393.51)] - [-1130.94 + 2(-373.21) + 4(-296.90)] = \boxed{-1867.54 \text{ kJ}}$$

i. Basis: 1 g mol CS₂ (l)

$$\Delta H^\circ_{\text{rxn}} = (-1394.69 - 60.25) - (+87.86) = \boxed{-287.61 \text{ kJ}}$$

j. Basis: 1 g mol C₂H₂ (g)

$$\Delta H^\circ_{\text{rxn}} = (+105.02) - (52.28 - 92.31) = \boxed{-145.05 \text{ kJ}}$$

k. Basis: 1 g mol CH₃OH (g)

$$\Delta H^\circ_{\text{rxn}} = (-115.90 - 241.82) - (-201.25) = \boxed{-156.48 \text{ kJ}}$$

l. Basis: 1 g mol C₂H₂ (g)

$$\Delta H^\circ_{\text{rxn}} = (-140.7) - (226.75 - 285.84) = \boxed{-81.61 \text{ kJ}}$$

m. Basis: 1 g mol C₄H₁₀ (g)

$$\Delta H^\circ_{\text{rxn}} = (52.28 - 84.67) - (-124.73) = \boxed{92.34 \text{ kJ}}$$

25.11

Basis: 1 g mol FeS₂

$$\Delta H^\circ_{\text{rxn}} = -567.4 \text{ kJ/g mol FeS}_2$$

$$\frac{(-567.4 \text{ kJ})}{\text{g mol FeS}_2} \left| \frac{1 \text{ g mol FeS}_2}{120 \text{ g FeS}_2} \right| \frac{1000 \text{ g}}{1 \text{ kg}} = -4728.3 \frac{\text{kJ}}{\text{kg FeS}_2}$$

Note: The information about conversion does not affect the value of the standard heat of reaction. It will affect the values in the energy balance.

25.12

 $\Delta \hat{H}_f^\circ$ of Fe₂O₃ is calculated as follows.

$$(1) \quad \Delta H_{\text{Rxn}} = \sum_{\text{products}} n_i \Delta \hat{H}_{f,i}^\circ - \sum_{\text{reactants}} n_i \Delta \hat{H}_{f,i}^\circ$$

$$-822.200 \text{ kJ} = \Delta \hat{H}_{f,\text{Fe}_2\text{O}_3}^\circ - \Delta \hat{H}_{f,\text{Fe}}^\circ (2) - \Delta \hat{H}_{f,\text{O}_2}^\circ \left(\frac{3}{2}\right)$$

(continued)

$$= \Delta \hat{H}_{f, H_2O(l)}^{\circ} - 0 - 0$$

$$(2) \quad \Delta H_{Rxn} = -284.100 \text{ kJ}$$

$$= \Delta \hat{H}_{f, H_2O(l)}^{\circ} - \Delta \hat{H}_{f, CO_2}^{\circ} (2) - \Delta \hat{H}_{f, C_6H_{12}O_6}^{\circ} \left(\frac{1}{2}\right)$$

$$-284.100 = -822.200 - \Delta \hat{H}_{f, CO_2}^{\circ} (2) - 0 \left(\frac{1}{2}\right)$$

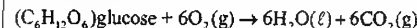
$$\Delta \hat{H}_{f, CO_2}^{\circ} = \frac{-538.10}{2} \text{ kJ} = \boxed{-269.05 \text{ kJ}}$$

vs ~ 267 in Appendix F

25.13

The problem requires more information to solve. To make the solution easier but approximate, assume the reaction takes place at 25°C and 1 atm. Assume that the energy balance reduces to $Q = \Delta H$, and that Q represents the desired kJ. Data:

$\Delta \hat{H}_{f, H_2O}^{\circ} = -285.840$ $\Delta \hat{H}_{f, CO_2}^{\circ} = -393.51$, both in kJ/g mol. Ref. temp. = 25°C. Basis: 1 g mol glucose. MW of glucose = 180.



$$\Delta H^{\circ} = \Delta H_{\text{products}}^{\circ} - \Delta H_{\text{reactants}}^{\circ}$$

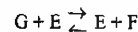
$$= [6(-285.840) + 6(-393.51)] - [1(-1260) + 6(0)] = -2816 \text{ kJ}$$

$$\frac{0.90(-2816)}{180} = \boxed{14.0 \text{ kJ/g glucose}}$$

At 37°C (body temperature), assume only the O_2 is used in a reaction

$$\frac{6 \text{ g mol } O_2}{1 \text{ g mol suc.}} \left| \frac{22.4 \text{ L at SC}}{\text{g mol } O_2} \right| \left| \frac{310 \text{ K}}{273 \text{ K}} \right| \left| \frac{1 \text{ g mol suc.}}{180 \text{ g suc.}} \right| = \boxed{0.85 \text{ L/g at } 37^{\circ}\text{C and } 1 \text{ atm}}$$

25.14



$\Delta \hat{H}_{Rxn}^{\circ}$ is at 25°C, 1 atm

$$\Delta \hat{H}_{Rxn}^{\circ} = \sum_{\text{prod.}} \Delta \hat{H}_f^{\circ} - \sum_{\text{react.}} \Delta \hat{H}_f^{\circ} = (1.040 \times 10^9 - 0.990 \times 10^9) / \text{g mol G}$$

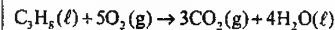
$$= \boxed{50 \times 10^6 \text{ J/g mol G converted}}$$

Since 0.48 reacts, $\Delta H_{Rxn}^{\circ} = 0.48(50) \times 10^6 \text{ J/g mol G}$

$$= 24 \times 10^6 \text{ J/g mol G fed (not asked for)}$$

25.15

The reaction is



Need to calculate the heat of formation of $C_3H_8(l)$ and $H_2O(l)$ first



$$\Delta \hat{H}_{f, C_3H_8(l)}^{\circ} = \Delta \hat{H}_{f, C_3H_8(g)}^{\circ} - \Delta \hat{H}_{\text{vap}}^{\circ}(25^{\circ}\text{C})$$

$$= -24.820 - 3.820 = -28.643 \text{ k cal/g mol}$$



$$\Delta \hat{H}_{f, H_2O(l)}^{\circ} = \Delta \hat{H}_{f, H_2O(g)}^{\circ} - \Delta \hat{H}_{\text{vap}}^{\circ}(25^{\circ}\text{C})$$

$$= -57.798 - 10.519 = -68.317 \text{ k cal/g mol}$$

(continued)

Basis: 1 g mol C_3H_8 (ℓ)

$$\Delta H_{Rn, C_3H_8(\ell)} = 4(-68.317) + 3(-94.052) - (-28.643) = \boxed{-526.781 \text{ k cal/g mol}}$$

25.16

a.

Presumably H_2 , O_2 , Cl_2 , HCl , and H_2O are gases.

$$(1) \quad 6 \text{ g mol } FeCl_3 (-403.34 \text{ kJ/g mol } FeCl_3) + 9 \text{ g mol } H_2O (-241.826 \text{ kJ/g mol } H_2O) \\ - 3 \text{ g mol } Fe_2O_3 (-822.156 \text{ kJ/g mol } Fe_2O_3) - 18 \text{ g mol } HCl (-92.312 \text{ kJ/g mol } HCl)$$

$$= \boxed{-468.39 \text{ kJ}}$$

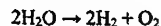
$$(2) \quad 6 \text{ g mol } FeCl_2 (-342.67 \text{ kJ/g mol } FeCl_2) + 3 \text{ g mol } Cl_2 (0.0 \text{ kJ/g mol } Cl_2) \\ - 6 \text{ g mol } FeCl_3 (-403.34 \text{ kJ/g mol } FeCl_3) = \boxed{364.02 \text{ kJ}}$$

$$(3) \quad 2 \text{ g mol } Fe_3O_4 (-1116.7 \text{ kJ/g mol } Fe_3O_4) + 12 \text{ g mol } HCl (-92.312 \text{ kJ/g mol } HCl) \\ + 2 \text{ g mol } H_2 (0.0 \text{ kJ/g mol } H_2) - 6 \text{ g mol } FeCl_2 (-342.67 \text{ kJ/g mol } FeCl_2) \\ - 8 \text{ g mol } H_2O (-241.826 \text{ kJ/g mol } H_2O) = \boxed{649.48 \text{ kJ}}$$

$$(4) \quad 3 \text{ g mol } Fe_2O_3 (-822.156 \text{ kJ/g mol } Fe_2O_3) - 2 \text{ g mol } Fe_3O_4 (-1116.7 \text{ kJ/g mol } Fe_3O_4) \\ - \frac{1}{2} \text{ g mol } O_2 (0.0 \text{ kJ/g mol } O_2) = \boxed{-233.07 \text{ kJ}}$$

$$(5) \quad 6 \text{ g mol } HCl (-92.312 \text{ kJ/g mol } HCl) + 3/2 \text{ g mol } O_2 (0.0 \text{ kJ/g mol } O_2) \\ - 3 \text{ g mol } H_2O (-241.826 \text{ kJ/g mol } H_2O) - 3 \text{ g mol } Cl_2 (0.0 \text{ kJ/g mol } Cl_2) = \boxed{171.61 \text{ kJ}}$$

b.

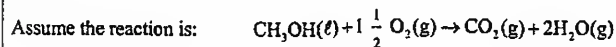


$$\sum \Delta H_{f, a}^\circ = \boxed{483.65 \text{ kJ}}$$

25.17

Basis: 1 g gasoline

$$\Delta H = \frac{40 \text{ kJ}}{\text{g}} \left| \frac{0.84}{\text{cm}^3} \right| = 33.6 \text{ kJ/cm}^3$$

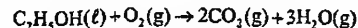
Methanol:

$$\Delta \hat{H}_f^\circ (\text{kJ/g mol}) \quad -238.64 \quad 0 \quad -393.51 \quad -241.826$$

$$\Delta H_{Rn} = -638.52 \text{ kJ/g mol}$$

$$\frac{638.52 \text{ kJ}}{\text{g mol}} \left| \frac{1 \text{ g mol}}{32.04 \text{ g}} \right| \left| \frac{0.792 \text{ g}}{\text{cm}^3} \right| = 15.79 \text{ kJ/cm}^3$$

$$\frac{33.6 \text{ kJ}}{\text{cm}^3 \text{ gas}} \left| \frac{\text{cm}^3 \text{ methanol}}{15.79 \text{ kJ}} \right| = 2.13 \frac{\text{cm}^3 \text{ methanol}}{\text{cm}^3 \text{ gas}} \quad \text{a. } (2.13-1) 100 = \boxed{113\% \text{ larger tank}}$$

Ethanol:

$$\Delta \hat{H}_f^\circ (\text{kJ/g mol}) \quad -277.63 \quad 0 \quad -393.51 \quad -241.828$$

$$\Delta H_{Rn} = -1235 \text{ kJ/g mol}$$

$$\frac{1235}{\text{g mol EtOH}} \left| \frac{1 \text{ g mol}}{46.07 \text{ g}} \right| \left| \frac{0.789 \text{ g}}{\text{cm}^3} \right| = 21.15 \text{ kJ/cm}^3$$

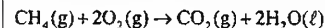
(continued)

$$\frac{33.6 \text{ kJ}}{\text{cm}^3 \text{ gas}} \left| \frac{\text{cm}^3 \text{ EtOH}}{21.15 \text{ kJ}} \right| = 1.59$$

$$\text{b. } (1.59) 100 - 100 = \boxed{59\% \text{ larger}}$$

25.18

No The value reported is the heat transfer for constant volume, Q_v . The heating value at constant pressure should be reported for the standard heat of reaction (an enthalpy change). Assume the reaction is at 25°C.



Basis: 1 g mol CH_4

$$Q = \Delta U = \Delta H - \Delta(pV)$$

If the gases can be treated as ideal $\Delta(pV) = \Delta(nRT) = \Delta n(RT)$.

$$\Delta n = 1 - 2 - 1 = -2$$

The correction is

$$\Delta nRT = -2(8.314)(298) = -4958 \text{ J/g mol}$$

In SI units of 273.15 K and 101.3 kPa, the volume is 22.415 m³ g mol.

The correction is (ignoring the pressure change from 1000 kPa to p_2)

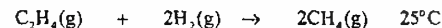
$$\frac{-4958}{22.415} = 221.2 \text{ J/m}^3 \text{ or } 0.22 \text{ kJ/m}^3$$

Otherwise you have to calculate $p_2V - p_1V$ where $p_2 = 1000 \text{ kPa}$ and $p_1 = p_{\text{H}_2\text{O}}^* + p_{\text{CO}_2}$.

$$\text{The value to be reported should be } 39.97 - 0.22 = \boxed{39.75 \text{ kJ/m}^3}$$

25.19

Basis: 1 g mol $\text{C}_2\text{H}_4(\text{g})$



$$\Delta \hat{H}_f^\circ \left(\frac{\text{kJ}}{\text{g mol}} \right) \quad 52.283 \quad 0 \quad -74.84$$

$$\Delta \hat{H}_{\text{rxn}}^\circ = 2(-74.84) - 52.283 = -202.0 \text{ kJ/g mol}$$

The reaction gives $Q = \Delta U = \Delta H - \Delta(pV)$. Assume ideal gases so that $\Delta(pV) = \Delta(nRT) = \Delta n(RT)$

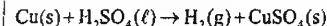
$$Q = -202.0 - (-1)(8.31 \times 10^{-3})(298)$$

$$\boxed{Q = -199.5 \text{ kJ/g mol}}$$

25.20

Basis: 1 g mol Cu and 1 g mol H_2SO_4

Data from Perry



$$\Delta \hat{H}_{\text{rxn}}^\circ = (0 - 772.78) - (0 - 810.40) = 37.61 \text{ kJ}$$

For a constant volume process:

$$Q = \Delta U = \Delta H - \Delta(pV) = \Delta H - \Delta n(RT) \quad \Delta n = 1$$

$$Q = 37.61 - (1)(8.314 \times 10^{-3})(298) = 35.13 \text{ kJ/g mol}$$

(continued)

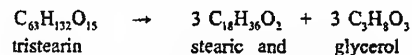
Basis: 1 lb mol of each reactant

$$\frac{(37.13)(1000)\text{J}}{\text{g mol}} \left| \frac{454\text{ g}}{1\text{ lb}} \right| \left| \frac{1\text{ Btu}}{1055\text{ J}} \right| = \boxed{15,978\text{ Btu/lb mol}}$$

25.21

Yes. Calculate the sensible heats using the tables and using a common reference temperature.

25.22



$$\Delta \hat{H}_{\text{rxn}}^{\circ} = -[(3)(-964.3) + (3)(-159.16)] - (-3820)(1) = \boxed{-449.6\text{ kJ/g mol}}$$

25.23

- If the exit temperature is $> 25^{\circ}\text{C}$, and the diluent is at the entering temperature of the reactants, then less heat has to be removed from the process.
- Remains the same as the presumption is in calculating $\Delta \hat{H}_{\text{rxn}}^{\circ}$ that stoichiometric quantities react to completion.
- At 25°C , $\Delta \hat{H}_{\text{rxn}}^{\circ} = \Delta \hat{H}_f^{\circ}$ with $\text{H}_2\text{O}(\text{g}) = -241.826\text{ kJ/g mol H}_2\text{O}$.

At 500 K, the sensible heats have to be considered, and $\frac{1}{2}\text{O}_2$ and H_2 together have a larger $\Delta \hat{H}$ than does H_2O so that $\Delta \hat{H}_{\text{rxn}}$ at 500 K is less than $\Delta \hat{H}_{\text{rxn}}$ at 25°C .

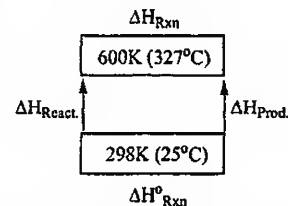
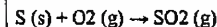
25.24

Yes (just the enthalpy of formation in the standard state is fixed).

25.25

No. $\Delta \hat{H}_f^{\circ}$ is arbitrarily assigned a value of 0 at the reference temperature.

25.26

Basis: 1 g mol S(s) = 1 g mol SO₂(g)

$$\Delta \hat{H}_{\text{rxn}, 600\text{ K}} = \Delta \hat{H}_{\text{rxn}}^{\circ} + \sum \Delta \hat{H}_{\text{prod}, 600\text{ K}} - \sum \Delta \hat{H}_{\text{react}, 600\text{ K}}$$

$$\Delta \hat{H}_{\text{rxn}, 298}^{\circ} = \sum_{\text{prod}} \Delta \hat{H}_f^{\circ} - \sum_{\text{react}} \Delta \hat{H}_f^{\circ}$$

$$= [-296.90] - [0 + 0] = -296.90\text{ kJ/g mol S}$$

$$= -296,900\text{ J/g mol S}$$

$$\sum \Delta \hat{H}_{\text{prod}, 600\text{ K}}$$

(continued)

$$\Delta H_{\text{SO}_2, 600 \text{ K}} = \int_{25}^{327} (38.91 + 3.904 \times 10^{-2} T - 3.104 \times 10^{-5} T^2 + 8.606 \times 10^{-9} T^3) dT$$

$$= 13,490 \text{ J/g mol} \quad (13,530 \text{ from Enthalpy Tables})$$

$$\sum \Delta H_{\text{react}, 600 \text{ K}}$$

This assumes s is really a liquid at 600°C , not a solid as in the equation

$$\Delta H_{\text{S}, 600 \text{ K}} = \Delta H_{\text{solid}, 298-386} + \Delta H_{\text{fusion}} + \Delta H_{\text{liquid}, 386-600}$$

$$= \int_{298}^{386} (15.2 + 2.68 \times 10^{-2} T) dT + 10,000 + 1/2 \int_{386}^{600} (35.90 + 1.26 \times 10^{-2} T) dT$$

$\frac{1}{2} (\text{S}_2 \text{ from Perry})$

$$= 2144 + 10,000 + 3975$$

$$= 16,119 \text{ J/g mol}$$

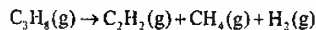
$$\Delta H_{\text{O}_2, 600 \text{ K}} = \int_{25}^{327} (29.10 + 1.158 \times 10^{-2} T - 0.6076 \times 10^{-5} T^2 + 1.311 \times 10^{-9} T^3) dT$$

$$= 9,340 \text{ J/g mol} \quad (8899 \text{ from the enthalpy tables})$$

$$\Delta H_{\text{rxn}, 600 \text{ K}} = -296,900 + (13,490 - 25,429)$$

$$= \boxed{308,840 \text{ J/g mol S}}$$

25.27



Basis: 1 g mol C_3H_8

$$\Delta H_{\text{SO}_2} = \Delta H_{25} + \sum \Delta H_{\text{prod}} - \sum \Delta H_{\text{react}}$$

$$\Delta H_{25}^0 = 226.75 + (-74.84) + 0 - (-103.85) = 255.76 \text{ kJ/g mol}$$

$$\Delta H = \int C_p dT = aT + b/2 T^2 + c/3 T^3 + d/4 T^4$$

$$\Delta H_{\text{C}_2\text{H}_2} = 68.032T + 1.130 \times 10^{-1} T^2 - 4.37 \times 10^{-5} T^3 + 7.928 \times 10^{-9} T^4 \Big|_{25}^{500}$$

$$= 55.53 \text{ kJ/g mol}$$

$$\Delta H_{\text{C}_2\text{H}_4} = 42.43 T + 3.027 \times 10^{-2} T^2 - 1.678 \times 10^{-5} T^3 + 4.55 \times 10^{-9} T^4 \Big|_{25}^{500}$$

$$= 25.89 \text{ kJ/g mol}$$

$$\Delta H_{\text{CH}_4} = 34.31 T + 2.735 \times 10^{-2} T^2 + 1.220 \times 10^{-6} T^3 + 2.75 \times 10^{-9} T^4 \Big|_{25}^{500}$$

$$= 23.10 \text{ kJ/g mol}$$

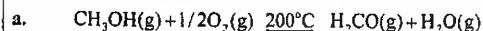
$$\Delta H_{\text{H}_2} = 28.84 T + 3.825 \times 10^{-5} T^2 + 1.096 \times 10^{-6} T^3 + 2.175 \times 10^{-10} T^4 \Big|_{25}^{500}$$

$$= 13.83 \text{ kJ/g mol}$$

$$\Delta H_{500} = (255.76 + 25.89 + 23.10 + 13.83) - 55.53 = \boxed{263.05 \text{ kJ/g mol}}$$

25.28

All data is from Tables E.1 and F.1 of the Appendix.



Basis: 1 g mol CH_3OH

(continued)

Comp.	C_p (J/(g mol)(K or °C))	T	$\Delta \hat{H}_f^\circ$ (kJ/g mol)
CH ₃ OH(g)	$42.39 + 8.301 \times 10^{-2}T - 1.87 \times 10^{-5}T^2 - 8.03 \times 10^{-9}T^3$	°C	-201.25
O ₂ (g)	$29.10 + 1.158 \times 10^{-2}T - 0.6076 \times 10^{-5}T^2 + 1.311 \times 10^{-9}T^3$	°C	0
H ₂ CO(g)	$34.28 + 4.268 \times 10^{-2}T - 8.694 \times 10^{-5}T^2$	°C	-115.89
H ₂ O(g)	$33.46 + 0.6880 \times 10^{-2}T + 0.7604 \times 10^{-5}T^2 - 3.593 \times 10^{-9}T^3$	°C	-241.826
	25°C = 298 K		
	200°C = 473 K		
$\Delta H^\circ_{\text{rxn}, 25^\circ\text{C}} = [-115.89 + (-241.826)] - (-201.25) = -156.47 \text{ kJ/g mol}$			
$= -156,470 \text{ J/g mol}$			
<u>Products</u>			
Add the C_p equations for the two products and integrate (each involves 1 mole).			
$\Sigma \Delta \hat{H}_{\text{prod}, 200^\circ\text{C}} = \int_{25}^{200} (67.74 + 4.95 \times 10^{-2}T + 0.7604 \times 10^{-5}T^2 - 1.228 \times 10^{-9}T^3) dT$			
$= 12,850 \text{ J/g mol}$			
<u>Reactants</u>			
$\Delta \hat{H}_{\text{CH}_3\text{OH}} = \int_{25}^{200} (42.39 + 8.301 \times 10^{-2}T - 1.87 \times 10^{-5}T^2 - 8.03 \times 10^{-9}T^3) dT$			
$= 9000 \text{ J/g mol}$			

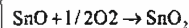
$\Delta \hat{H}_{\text{O}_2} = \frac{1}{2} \int_{25}^{300} (29.10 + 1.158 \times 10^{-2}T - 0.6076 \times 10^{-5}T^2 + 1.311 \times 10^{-9}T^3) dT$			
$= 2,650$			
$\Delta \hat{H}_{\text{rxn}, 300^\circ\text{C}} = -156,470 + 12,850 - 2,650 = \boxed{146,270 \text{ J/g mol}}$			
b. $\text{SO}_2(\text{g}) + 1/2 \text{O}_2(\text{g}) \xrightarrow{300^\circ\text{C}} \text{SO}_3(\text{g})$			
Basis: 1 g mol SO ₂			
Comp.	C_p (J/(g mol)(K or °C))	T	$\Delta \hat{H}_f^\circ$ (kJ/g mol)
O ₂ (g)	$29.10 + 1.158 \times 10^{-2}T - 0.6076 \times 10^{-5}T^2 + 1.311 \times 10^{-9}T^3$	°C	0
SO ₂ (g)	$38.91 + 3.904 \times 10^{-2}T - 3.104 \times 10^{-5}T^2 + 8.606 \times 10^{-9}T^3$	°C	-296.90
SO ₃	$48.50 + 9.188 \times 10^{-2}T - 8.540 \times 10^{-5}T^2 + 32.40 \times 10^{-9}T^3$	°C	-395.18
$\Delta H^\circ_{\text{rxn}, 25^\circ\text{C}} = -395.18 + 296.90 = -98.28 \text{ kJ/g mol} = -98,280 \text{ J/g mol}$			
<u>Products</u>			
$\Sigma \Delta \hat{H}_{\text{prod}, 300^\circ\text{C}} = \int_{25}^{300} (48.50 + 9.188 \times 10^{-2}T - 8.540 \times 10^{-5}T^2 + 32.40 \times 10^{-9}T^3) dT$			
$= 16,740 \text{ J/g mol}$			
<u>Reactants</u>			
$\Delta \hat{H}_{\text{SO}_2} = \int_{25}^{300} (38.91 + 3.904 \times 10^{-2}T - 3.104 \times 10^{-5}T^2 + 8.606 \times 10^{-9}T^3) dT$			
$= 12,180 \text{ J/g mol}$			
(continued)			

$$\Delta H_{O_2} = 8,470 \text{ J/g mol}$$

$$\Delta H_{\text{rxn}, 300^\circ\text{C}} = -98,280 + 16,740 - 12,180 - (8,470) \frac{1}{2} = \boxed{-97,960 \text{ J/g mol SO}_2}$$

25.29

Basis: 1 g mol SnO



$$\Delta H_{\text{rxn}, 25} = -577.8 - (-283.3 + 0) = -294.5 \text{ kJ/g mol}$$

$$\Delta H_{90} = \Delta H_{\text{rxn}, 25} + \sum \Delta H_{\text{prod}} - \sum \Delta H_{\text{react}}$$

$$\Delta H = \int_{25^\circ\text{C}}^{90^\circ\text{C}} C_p dT$$

$$\Delta H_{\text{SnO}} = 39.33T + 7.575 \times 10^{-3} T^2 \Big|_{25}^{90} = 2.88 \text{ kJ}$$

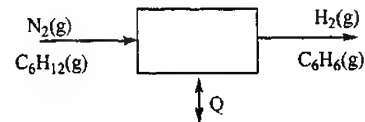
$$\Delta H_{\text{SnO}_2} = 73.89 T + 5.02 \times 10^{-3} T^2 + \frac{2.16 \times 10^4}{T} \Big|_{25}^{90} = 2.89 \text{ kJ}$$

$$\Delta H_{O_2} = 29.1 T + 5.79 \times 10^{-3} T^2 - 2.025 \times 10^{-6} T^3 + 3.278 \times 10^{-10} T^4 \Big|_{25}^{90} = 1.93 \text{ kJ}$$

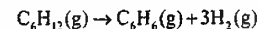
$$\Delta H_{90} = -294.5 + 2.89 - (2.88 + 0.5(1.93)) = \boxed{-295.46 \text{ kJ/g mol}}$$

25.30

Assume steady state flow process with reaction.



Ref. temp. = 25°C



The standard heat of reactions is

$$\Delta \hat{H}_{\text{rxn}}^\circ = [1(82,927) + 3(0)] - [1(-123,100)] = 2.06 \times 10^5 \text{ J/g mol C}_6\text{H}_{12}$$

Material balance:

Step 5: Basis: 1 g mol C₆H₁₂ (g) inSteps 6 to 9:Make balances for each species so that the unknowns H₂ and C₆H₆ can be calculated.

Results:	n_{H_2}	out	=	0.70(1)(3)	=	2.10	$n_{\text{C}_6\text{H}_6}$	in	=	1.0
	$n_{\text{C}_6\text{H}_6}$	out	=	0.70(1)(1)	=	0.70	n_{N_2}	in	=	0.50
	$n_{\text{C}_6\text{H}_{12}}$	out	=	0.30(1)	=	0.30				
	n_{N_2}	out	=	0.50						

Energy balance

(continued)

Solutions Chapter 25

Component	$\Delta \hat{H}_f^\circ$ (J/gmol)	$\int_0^T C_p dT$ (or use tables)*; T = 300°C	n_i	$\Delta \hat{H}_{T_i}^{300}$ (kJ)
Out:				
H ₂ (g)	0	8031	0	2.10
C ₆ H ₆ (g)	+ 82,927 × 10 ³	18,824	or	0.70
C ₆ H ₁₂ (g)	- 123.1 × 10 ³	35,408	0	0.30
N ₂ (g)	0	8,031	0	0.50
				<u>4.016</u>
				<u>44,556</u>
In:				
C ₆ H ₁₂ (g)	-123.1 × 10 ³	0	or	0
N ₂ (g)	0	0	0	0.50
				<u>0</u>
				<u>-123.1</u>

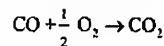
(a) $Q = 1.44 \times 10^5 \text{ J/gmol}$ (b) $Q = +1.68 \times 10^5 \text{ J/gmol}$

*at 25°C exit temp. and entrance temp. these terms are 0.

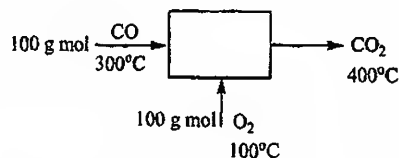
25.31

Basis: 100 g mol CO

Assume pressure is 1 atm, and an open, steady state process.



The energy balance reduces to $Q = \Delta H$. The reference temperature is 25°C.



Data:

Solutions Chapter 25

Comp.	mol	T(°C)	Sensible heats		
			$\Delta \hat{H}_f^\circ$ (kJ / g mol)	from CD : $\Delta \hat{H}$ (kJ / g mol)*	ΔH (kJ)
<u>In</u>					
O ₂	100	100	-	2.235	223.5
CO	100	300	-110.541	8.294	-10,225
<u>Out</u>					
O ₂	50	400	-	11.715	585.8
CO ₂	100	400	-393.505	16.245	-37,726

*You can calculate $\Delta \hat{H}_{\text{sensible}}$ using the tables in the appendix, but the process requires interpolation.

$$Q = \Delta H = (-37,726 + 585.8) - (-10,225 + 223.5) = \boxed{-27,139 \text{ kJ}}$$

25.32

Basis: 1 gal of each fuel

	MW	density (g/cm ³)
(1) Ethanol : C ₂ H ₅ OH(l) + 3O ₂ (g) → 2CO ₂ (g) + 3H ₂ O(l)	46	0.789
(2) Benzene : C ₆ H ₆ (l) + 7.5O ₂ (g) → 6CO ₂ (g) + 3H ₂ O(l)	78	0.879
(3) Isooctane : C ₈ H ₁₈ (l) + 12.5O ₂ (g) → 8CO ₂ (g) + 9H ₂ O(l)	114	0.692

Example calculation

$$\text{Benzene: } \frac{1 \text{ gal Bz}}{\text{cm}^3 \text{ Bz}} \left| \frac{0.879 \text{ g Bz}}{1 \text{ gal}} \right| \left| \frac{3.785 \text{ L}}{1 \text{ gal}} \right| \left| \frac{1000 \text{ cm}^3}{1 \text{ L}} \right| \left| \frac{1 \text{ g mol Bz}}{78 \text{ g Bz}} \right| \left| \frac{6 \text{ g mol CO}_2}{1 \text{ g mol Bz}} \right|$$

$$\times \frac{44 \text{ g CO}_2}{1 \text{ g mol CO}_2} \left| \frac{1 \text{ lb}}{454 \text{ g}} \right| = \boxed{24.8 \text{ lb CO}_2 / \text{gal Bz}}$$

(continued)

Other results:Ethanol: $12.5 \text{ lb CO}_2 / \text{gal EtOH}$ Isooctane: $17.8 \text{ lb CO}_2 / \text{gal iso}$

Carry out the standard combustion material balance for stoichiometric air. The ratios are at SC or the same temperature and pressure.

Example of the calculation for benzene (Reaction 2)

Use data from the CD, heat capacity equations, or tables to get the sensible heats. The data below are from the CD. Reference $T = 25^\circ\text{C}$.

IN:	$T(^{\circ}\text{C})$	mol	$\Delta\hat{H}_f^{\circ}(\text{kJ/g mol})$	$\Delta\hat{H}_{\text{sensible}}(\text{kJ/g mol})$	$\Delta H(\text{kJ})$
$\Delta H(\text{kJ})$					
$\text{C}_6\text{H}_6(\ell)$	25	1	+ 44.66	-	46.66
$\text{O}_2(\text{g})$	100	7.5	-	2.235	16.763
$\text{N}_2(\text{g})$	100	28.21	-	2.183	61.553
OUT:					
$\text{CO}_2(\text{g})$	25	6	-393.505	-	2361.030
$\text{H}_2\text{O}(\ell)$	25	3	-285.840	-	857.520
$\text{N}_2(\text{g})$	25	28.21	-	-	-

$$\Delta H_{\text{rxn}} = (-2361.030 - 857.520) - (46.66 + 16.763 + 61.553) = -3093.6 \text{ kJ/g mol Bz}$$

-3093.6 kJ	1 gal Bz	0.879 g Bz	3.785 L	1000 cm^3	1 g mol Bz	1 Btu
g mol Bz		$\text{cm}^3 \text{ Bz}$	1 gal	1 L	78 g Bz	1.055 kJ

$$= -1.251 \times 10^5 \text{ Btu per gal Bz} \quad (\text{exothermic})$$

Ethanol: $-7.55 \times 10^4 \text{ Btu per gal EtOH}$ Isooctane: $-1.21 \times 10^5 \text{ Btu per gal isooctane}$

	$\text{lb CO}_2 / 10^6 \text{ Btu}$
Ethanol	166
Benzene	198
Isooctane	147

25.33

Steady State, open process. Ref $T = 25^\circ\text{C}$

Basis: 100 g mol feed

The moles out come from the material balance, and the other data from the CD.

$$Q = \Delta H$$

 ΔH data from the CD.

Comp.	% = g mol	$T(^{\circ}\text{C})$	$\Delta\hat{H}_f^{\circ}(\text{kJ/g mol})$	$\Delta\hat{H}_{\text{sensible}}(\text{kJ})$	$\Delta H(\text{kJ})$
<u>IN with gas</u>					
CO_2	6.4	500	-393.505	20.996	-2384.06
O_2	0.2	500	-	15.034	3.04
CO	40.0	500	-110.541	14.690	-3834.04
H_2	50.8	500	-	13.834	702.77
N_2	2.6	500	-	14.242	37.03
	100.0				-5,475.29

(continued)

In with air

O ₂	63.28	25	-	0	0
N ₂	<u>240.65</u>	25	-	0	0
	303.93				

Out with fg

CO ₂	46.4	720	-393.505	32.006	-16,773.55
H ₂ O(g)	50.8	720	-241.835	26.133	-10,957.66
N ₂	240.65	720	-	21.242	5,111.89
O ₂	<u>18.1</u>	720	-	22.555	<u>408.25</u>
	356.0				-22,211.08

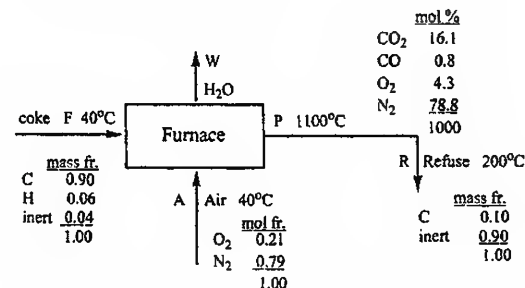
$$Q = \Delta H = (-22,211.08) - (-5,475.29) = \boxed{-16,736 \text{ kJ}}$$

(Heat leaving)

25.34

Steady state, open process. Ref T = 25°C

Basis: 100 g mol P



Data come from the material balances and the CD.

$$\frac{C_p (\text{J/g mol})(^\circ\text{C})}{\text{H } 20.8}$$

$$\text{C } 14.3$$

Comp.	Percent (g)	g mol	T(°C)	$\Delta \hat{H}_f^\circ (\text{kJ/g mol})$	$\Delta \hat{H}_{\text{sensible}} (\text{kJ/g mol})$	$\Delta H (\text{kJ})$
<u>In F (214.8 g) solid</u>						
C	90.0	16.11	40	-	0.214	3.456
H	6.0	12.79	40	-	0.312	3.991
Inert	<u>4.0</u>	<u>-</u>	40	-	ignore	-
	100.0	28.90				7.447

(continued)

In air (99.7 g mol)

O ₂	20.94	40	-	0.442	9.255
N ₂	<u>78.76</u>	40	-	0.436	<u>34.339</u>
	99.70				43.595

Out in P (g)

CO ₂	16.1	1100	-393.505	24.744	-5937.05
CO	0.8	1100	-110.541	25.032	-68.41
O ₂	4.3	1100	-	26.209	112.70
N ₂	<u>78.8</u>	1100	-	38.891	<u>3064.59</u>
	100.0				-2828.17
Water out (g)	6.80	1100	-241.826	30.174	205.18
Refuse	10 g	200	-	1.488 per g	14.88

$$Q = \Delta H = (-2828.17 + 205.18 + 14.88) - (7.447 + 43.595) = \boxed{-2659.2 \text{ kJ}}$$

(heat exiting)

25.35

Basis: 1 g mol CaCl₂ · 6H₂O(s)

Unsteady state, open process. Reference T = 25°C.

68°F → 20°C and 86°F → 30°C

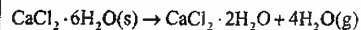
$$\Delta U = Q - \Delta H_{H_2O \text{ exiting}}$$

Assume $\Delta U = \Delta H$ inside the system

Data	$\Delta \hat{H}_f^\circ (\text{kJ/g mol})$	$C_p (J/(g)(^\circ C))$	MW
CaCl ₂ · 6H ₂ O(s)	-2607.89	1.34	219
CaCl ₂ · 2H ₂ O(s)	-1402.90	0.97	147

Calculate $\Delta \hat{U}$

Comp.	g mol	T(°C)	MW	$\Delta \hat{H}_f^\circ (\text{kJ/g mol})$	$\Delta H_{\text{available}} (J)$	$\Delta H (\text{kJ})$
<u>Initial</u>						
CaCl ₂ · 6H ₂ O(s)	1	20	219.1	-2607.89	(1)(1.34)(219.1)(25-20)	-2606.422
<u>Final</u>						
CaCl ₂ · 2H ₂ O(s)	1	30	129.0	-1402.90	(1)(0.97)(129.0)(30-25)	-1402.274
<u>Out</u>						
H ₂ O(g)	4	30	18.0	-241.826	(1)(4.18)(18)(30-25)	-965.798

Per g mol CaCl₂ · 6H₂O(s):

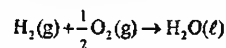
$$Q = \Delta U + \Delta H_{\text{exiting}} = [(-1402.274) - (-2606.422)] + (-965.798)$$

$$= 238 \text{ kJ} \quad \text{or} \quad 226 \text{ Btu/g mol CaCl}_2 \cdot 6\text{H}_2\text{O(s)}$$

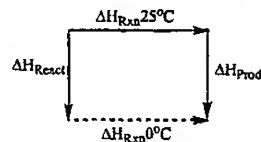
$$\frac{200,000 \text{ Btu}}{226 \text{ Btu}} \left| \frac{1 \text{ g mol CaCl}_2 \cdot 6\text{H}_2\text{O(s)}}{1 \text{ g mol}} \right| \frac{219 \text{ g}}{1000 \text{ g}} \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| = \boxed{194 \text{ kg}}$$

(427 lb)

25.36

At 25°C and 1 atm H₂O is a liquid.

$$\Delta H_f^\circ (\text{kJ/g mol}): -285.84 \quad 0 \quad 0$$

Basis: 1 g mol H₂ (g)

$$\Delta H_{rxn}^\circ = -[\sum \Delta H_{f, \text{Prod}}^\circ - \sum \Delta H_{f, \text{React}}^\circ]$$

$$= -[(1)(0) - (1)(-285.84) - (\frac{1}{2})(0)] = -285.84 \text{ kJ/g mol H}_2$$

H₂O at 25°C is a liquid

$$\Delta H_{Prod} = \int_{25^\circ\text{C}}^{0^\circ\text{C}} C_p dT = \frac{4.184 \text{ J}}{(\text{g})(^\circ\text{C})} \left| \frac{18 \text{ g}}{1 \text{ g mol}} \right| \frac{(-25^\circ\text{C})}{1} = -1.883 \text{ kJ}$$

$$\Delta H_{React} = (1) \int_{25^\circ\text{C}}^{0^\circ\text{C}} C_{p\text{H}_2(\text{g})} dT + (\frac{1}{2}) \int_{25^\circ\text{C}}^{0^\circ\text{C}} C_{p\text{O}_2(\text{g})} dT = -(718)(1) - (727)(\frac{1}{2}) = -1.081 \text{ kJ}$$

$$\Delta H_{rxn}(0^\circ\text{C}) = (-1.883) - (-1.081) + (-285.84) = \boxed{-286.64 \text{ kJ/g mol H}_2}$$

25.37

$$(a) \quad \text{HHV} = 14,544 (.80) + 62,028 \left(0.0003 - \frac{0.005}{8} \right) + 4050(0.006)$$

$$= 11,640 \text{ Btu/lb}$$

$$\text{LHV} = 11,800 - 91.23(0.3) = 11,770 \text{ Btu/lb}$$

$$(b) \quad \text{HHV} = 17,887 + 57.5(30) - 102.2(0.5) = 19,560 \text{ Btu/lb}$$

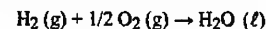
$$\text{LHV} = 19,560 - 91.23(12.05) = 18,460 \text{ Btu/lb}$$

25.38

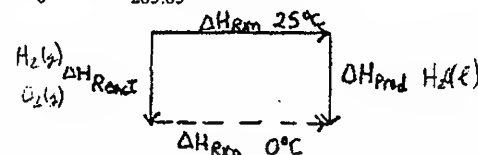
If the fuel cannot produce H₂O as a product, HHV = LHV, but the concept really refers to cases in which water is produced so that HHV ≠ LHV.

25.39

Both H₂ and O₂ enter at 0°C, and the products leave at 0°C. The reference temperature is 25°C. Stoichiometric quantities react according to the reaction equation.



$$\Delta H_f^\circ (\text{kJ/g mol}): \quad 0 \quad 0 \quad -285.83$$

Basis: 1 g mol H₂ (g)

(continued)

Solutions Chapter 25

$$\Delta H_{Rxn}(0^\circ\text{C}) = \Sigma \Delta H_{\text{Products}} - \Sigma \Delta H_{\text{Reactants}}$$

$$\Sigma \text{Products} = (-285.83) + \int_{25^\circ\text{C}}^{0^\circ\text{C}} \frac{4.184 \text{ J}}{\text{g}^\circ\text{C}} \left| \frac{18 \text{ g H}_2\text{O}}{\text{g mol}} \right| dT = -287.71 \text{ kJ}$$

Alternately you can use the steam tables or the CD to get the value. The reactants are gases, hence ΔH can be obtained from tables.

$$\Sigma \text{Reactants} = (0 + 0) + (1) \int_{25^\circ\text{C}}^{0^\circ\text{C}} (28.84 + 0.00765 \times 10^{-2} T) dT$$

$$+ \left(\frac{1}{2}\right) \int_{25^\circ\text{C}}^{0^\circ\text{C}} (29.10 + 1.158 \times 10^{-2} T) dT = -1.45 \text{ kJ}$$

$$\Delta H_{Rxn}(0^\circ\text{C}) = -287.71 - (-1.45) = \boxed{-286.26 \text{ kJ}}$$

25.40

Basis: 100 lb mol gas

The reaction for each compound is the stoichiometric amount of O_2 going to CO_2 gas and H_2O (ℓ)

Comp.	lb mol	$\Delta \hat{H}$ (Btu/lb mol)	ΔH (Btu)
CO_2	9.2	0	0
C_2H_4	0.4	598,000	239,000
CO	20.9	122,000	2,544,000
H_2	15.6	123,000	1,918,000
CH_4	1.9	383,000	728,000
N_2	<u>52.0</u>	0	0
	100.0		5,429,000

Note: NGI standard state is 60°F

$$\frac{\text{Btu}}{\text{ft}^3} = \frac{5,429,000 \text{ Btu}}{100 \text{ lb mol}} \left| \frac{1 \text{ lb mol}}{359 \text{ ft}^3} \right| \frac{520^\circ\text{R}}{492^\circ\text{R}}$$

Solutions Chapter 25

$$= \boxed{143 \text{ Btu / ft}^3 \text{ at std. conditions of NGI}}$$

25.41

Basis: 1 m^3 gas at 25°C and 1 atm with 40% relative saturation

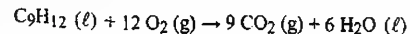
Calculate the moles of C_9H_{12} gas. Its pressure at 25°C is calculated as follows:
($P_{\text{H}_2\text{O}} = 3.2 \text{ kPa}$)

$(3.2)(0.40) = 1.28 \text{ kPa}$, and thus the pressure of the C_9H_{12} (g) is $(101.3 - 1.28) = 100 \text{ kPa}$.

$$n = \frac{pV}{RT} = \frac{100 \text{ kPa}}{1 \text{ atm}} \left| \frac{1 \text{ m}^3}{298 \text{ K}} \right| \frac{1(\text{kg mol})(\text{K})}{8.314(\text{kPa})(\text{m}^3)} = 0.0404 \text{ kg mol}$$

Basis: 1 g mol n-propyl benzene ($\text{C}_6\text{H}_5 \cdot \text{CH}_2 \cdot \text{C}_2\text{H}_5$)

The higher heating value is with H_2O as a liquid. Also, at 25°C , C_9H_{16} is a liquid; its normal boiling point is 432 K .



$$\Delta \hat{H}_f^\circ \left(\frac{\text{kJ}}{\text{g mol}} \right): \quad -38.40 \quad 0 \quad -393.51 \quad -285.840$$

$$\Delta \hat{H}_{Rxn}^\circ = [6(-285.840 + 9(-393.51))] - [(1)(-38.40)]$$

$$= -5218.2 \text{ kJ/g mol C}_9\text{H}_{12}$$

$$\text{HHV} = -\frac{5218.2 \text{ kJ}}{\text{g mol C}_9\text{H}_{12}} \left| \frac{40.4 \text{ g mol C}_9\text{H}_{12}}{1 \text{ m}^3 \text{ gas}} \right| = \boxed{2.11 \times 10^5 \text{ kJ/m}^3}$$

25.42

Basis: 100 mol of gas

(a1)

Comp.	mol.wt.	Mol% Vol.%	lb	$-\Delta H^\circ_{c1}$ kJ/g mol	$-\Delta H^\circ_{c2}$ kJ/g mol
CH ₄	16	88	1408	890.35	802.32
C ₂ H ₆	30	6	180	1559.88	1427.84
C ₃ H ₈	44	4	176	2220.05	2044.00
C ₄ H ₁₀	58	2	116	2878.52	2658.45
Total		100	1880		

mol. wt. mixture = 18.80 lb/lb mol

 $-\Delta H^\circ_c = \text{H}_2\text{O}(l) \text{ to } \text{CO}_2(g) \text{ products; } -\Delta H^\circ_c = \text{H}_2\text{O}(g) + \text{CO}_2(g) \text{ products}$

$$\Delta H^\circ_{1 \text{ rxn}} = -[\Delta H_c \text{ prod} - \Delta H^\circ_c \text{ react}] = 1022.90 \text{ kJ/g mol}$$

$$(a1) \quad \Delta H^\circ_{\text{rxn}} = \frac{-1022.90}{\text{g mol}} \left| \frac{454 \text{ g mol}}{\text{lb mol}} \right| \left| \frac{\text{Btu}}{1.055 \text{ kJ}} \right| \left| \frac{\text{lb mol}}{18.80 \text{ lb}} \right| = -23,600 \frac{\text{Btu}}{\text{lb}}$$

$$\boxed{\text{HHV} = 23,600 \text{ Btu/lb}}$$

$$(a2) \quad \Delta H^\circ_{\text{rxn}} = (-23,600)(18.80) = -439,000 \text{ Btu / lb mol}$$

$$\boxed{\text{HHV} = 439,000 \text{ Btu/lb mol}}$$

$$(a3) \quad \Delta H^\circ_{\text{rxn}} = \frac{-439,000 \text{ Btu}}{\text{lb mol}} \left| \frac{1 \text{ lb mol}}{379.2 \text{ ft}^3 \text{ at } 60^\circ\text{F, } 760 \text{ mm Hg}} \right| = -1160$$

$$\text{HHV} = \boxed{1160 \text{ Btu / ft}^3 \text{ at } 60^\circ\text{F, } 760 \text{ mm Hg}}$$

$$(b1) \quad \Delta H^\circ_{2 \text{ rxn}} = -925.71 \text{ kJ/g mol}$$

$$\Delta H^\circ_{2 \text{ rxn}} = \frac{-925.71}{1.055} \left| \frac{454}{18.80} \right| = -21,200 \text{ Btu/lb}$$

$$\boxed{\text{LHV} = 21,200 \text{ Btu/lb}}$$

$$(b2) \quad \Delta H^\circ_{2 \text{ rxn}} = (-21,200)(18.80) = \boxed{-398,000 \text{ Btu/lb mol}}$$

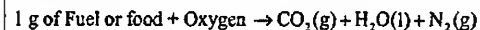
$$\boxed{\text{LHV} = 398,000 \text{ Btu / lb mol}}$$

$$(b3) \quad \Delta H^\circ_{2 \text{ rxn}} = (-398,000)/(379.2) = -1051$$

$$\boxed{\text{LHV} = 1051 \text{ Btu/ft}^3 \text{ at } 60^\circ\text{F and } 760 \text{ mm Hg}}$$

25.43

Write the equation for the combustion for 1 gram as:



Both the reactants and the products are at 25°C and 1 atm. The chemical energy released by the complete combustion of 1 g of a food or fuel according to the above equation at standard conditions is the heat of combustion. Assume the ΔH_c are additive. Then

$$\Delta H_c = (17.1)(28) + (39.5)(10) + (14)(4) = 930 \text{ kJ}$$

The High Energy bar has (capital C for calorie)

$$\frac{220 \text{ Calories}}{1 \text{ Calorie}} \left| \frac{1000 \text{ calories}}{1 \text{ calorie}} \right| \left| \frac{4.184 \text{ J}}{1 \text{ calorie}} \right| \left| \frac{1 \text{ kJ}}{1000 \text{ J}} \right| = 921 \text{ kJ}$$

The values are close enough.

25.44

When the combustion results in a single component.

25.45

Basis: 1 lb mixture

Get the data for the ΔH_c in Btu/lb, not Btu/mol.

Component	Mass fr., ω_i	ΔH_c (Btu / lb)	ΔH (Btu)	Basis 1200 lb
Hexachloroethane, C_2Cl_6	0.0487	828	40	58.44
Tetrachloroethene, C_2Cl_4	0.0503	2141	108	60.36
Chlorobenzene, C_6H_5Cl	0.2952	11,876	3,506	354.24
Toluene, C_7H_8	<u>0.6058</u>	18,246	<u>11,053</u>	<u>726.96</u>
Total	1.000		14,707	1200.00

The Btu/lb are 14,707 from the heat of combustion data, a deviation of 3.2% from 15,200. For DuLong's equation, the component elements are needed.

Basis: 1200 lb

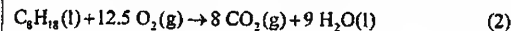
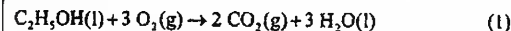
	C	H	Cl	O	MW	Total (lb)
C_2Cl_6	24	0	213	0	237.00	
ω_i	0.10	0.00	0.90	0.00		
lb	5.84	0.00	52.60	0.00		58.44
C_2Cl_4	24	0	142	0	166.00	
ω_i	0.14	0.00	0.86	0.00		
lb	8.45	0.00	51.91	0.00		60.36
C_6H_5Cl	72	5	35.5	0	112.50	
ω_i	0.64	0.04	0.32	0.00		
lb	226.71	14.17	113.36	0.00		354.24
C_7H_8	84	8	0	0	92.00	
ω_i	0.91	0.09	0.00	0.00		
lb	661.53	65.43	0.00	0.00		726.91
Total	902.53	79.60	217.87	0		1200
ω_i	0.75	0.07	0.18	0		1.00
HHV = 14,455 C + 62,028 H - 7753.5O ₂ + 4050 S						(continued)

$$= (14,455)(0.75) + (62,028)(0.07)$$

$$= \boxed{15,183} \text{ Btu/lb (the higher heating value) a deviation of 0.11\%}$$

25.46

The reactions are:



$$\Delta H_{\text{rxn}} = - \left[\sum_{\text{products}} n_i \Delta \hat{H}_{\text{c},i}^\circ - \sum_{\text{reactants}} n_i \Delta \hat{H}_{\text{c},i}^\circ \right]$$

$$\text{For (1): } -[(2)(0) + (3)(0) - (3)(0) - (1)(-1366.91)] = -1366.91 \text{ kJ/g mol C}_2\text{H}_5\text{OH}$$

$$\text{For (2): } -[(8)(0) + (9)(0) - (12.5)(0) - (-1307.53)(4.184)] = -5470.71 \text{ kJ/g mol C}_8\text{H}_{18}$$

Note: the $\Delta \hat{H}_{\text{c}}^\circ = 1307.53 \text{ kcal/g mol}$ for n-octane liquid is from Perry.

Basis: 1 kg gasahol

Component	mass.fr. = kg	MW	g mol	$\Delta \hat{H}(\text{kJ})$
$\text{C}_2\text{H}_5\text{OH}$	0.10	46.05	2.17	-2,966
C_8H_{18}	<u>0.90</u>	114.14	7.89	-43,137
Total	1.00			<u>-46,103</u>

If the fuel were all octane

$$\frac{1 \text{ kg octane}}{114.14 \text{ kg octane}} \left| \frac{1 \text{ kg mol octane}}{1 \text{ kg}} \right| \frac{1000 \text{ g}}{\text{g mol octane}} \left| \frac{-5470.71 \text{ kJ}}{\text{g mol octane}} \right| = -47,930 \text{ kJ}$$

$$\frac{-47,930 - (-46,103)}{-47,930} (100) = \boxed{3.8\%}$$

25.47

Basis: 1 g mol dry cells

The heat of reaction is

$$\Delta H_{\text{rxn}}^\circ = - \left[\sum_{\text{products}} n_i \Delta \hat{H}_{\text{f},i}^\circ - \sum_{\text{reactants}} n_i \Delta \hat{H}_{\text{f},i}^\circ \right]$$

$$= -[(1)(-1,517) + 2.75(-393.51) + 3.42(-285.840)]$$

$$-6.67(-2,817) - 2.10(0)] = -15,213 \text{ kJ/g mol cells}$$

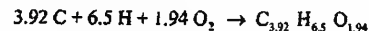
For 100 g dry cells

$$\frac{-15,213 \text{ kJ}}{\text{g mol dry cells}} \left| \frac{1 \text{ g mol}}{84.58 \text{ g dry cells}} \right| \frac{100 \text{ g dry cells}}{\text{g mol dry cells}} = \boxed{-1.800 \times 10^4 \text{ kJ}}$$

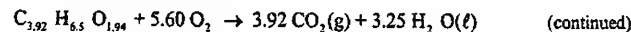
25.48

Basis: 1 g mol yeast

The heat of formation is



The heat of combustion is for the reaction



$$-1,518 \text{ kJ} = - \left[\sum_{\text{product}} n_i \Delta \hat{H}_{f,i}^{\circ} - \sum_{\text{reactants}} n_i \Delta \hat{H}_{f,i}^{\circ} \right]$$

$$-1,518 = - \left[(3.92)(-393.51) + (3.25)(-285.840) - 5.60(0) - (1) \Delta \hat{H}_{f,\text{yeast}}^{\circ} \right]$$

$$\Delta \hat{H}_{f,\text{yeast}}^{\circ} = -963.54 \text{ kJ/g mol}$$

The molecular weight of $\text{C}_{3.92}\text{H}_{8.5}\text{O}_{1.94}$ is 84.63. Per 100 g yeast

$$\Delta \hat{H}_{f,\text{yeast}}^{\circ} = \boxed{-1139 \text{ kJ/100 g yeast}}$$

25.49

Basis: The given data

	<u>$\Delta H(\text{kJ/g mol})$</u>	<u>g mol produced/g mol glucose</u>
Ethanol	-1330.51	0.94
Acetate	-887.01	1.05
Formate	-221.75	1.76
Lactate	-1330.51	0.05
Glucose	-2661.02	1.00 (consumed)

The enthalpy change in the solution was

$$\Delta H_{\text{rxn}} = \sum_{\text{products}} n_i \Delta H_i - \sum_{\text{reactants}} n_i \Delta H_i$$

$$= [(0.94)(-1330.51) + (1.05)(-887.01) + 1.76(-221.75)$$

$$+ 0.05(-1330.51)] - (1.00)(-2661.02) = \boxed{22.17 \text{ kJ/g mol glucose}}$$

$$\text{b. } \frac{22.17 \text{ kJ}}{\text{g mol glucose}} \left| \frac{1 \text{ g mol glucose}}{62 \text{ g cells}} \right| = \boxed{0.358 \text{ kJ/g cells}}$$

26.1

Assume that the furnace has to be ready to function at the operating temperature after 48 hours.

<u>Oil required at idle</u>		<u>L used</u>	
Operating for 48-hours:	270(48)=	12,960 × \$.19 =	\$2,462

Oil required for 6.5 hours of heating

Heating	60(6.5)	4,940 × \$.19 =	939
Difference			\$1,523

The problems may have to do with excessive maintenance on shutting the furnace down and starting it up. The insulation may be damaged.

26.2

Nitrogen, in general, does not react with other chemical species during a combustion process, although some NO_x forms, but its presence affects the outcome of the process because the sensible heat of nitrogen absorbs a large proportion of the energy released during the chemical process.

26.3

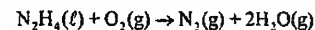
Moisture, in general, does not react chemically with any of the species present in the combustion chamber, but it absorbs some of the energy released during combustion, and it raises the dew point temperature of the combustion gases.

26.4

- (a) reduces
- (b) increases
- (c) reduces

26.5

The reaction is:



Calculate the material balance first:

Basis: 1 g mol N₂H₄

In		Out	
N ₂ H ₄	1	N ₂	1 + 2 $\left(\frac{79}{21}\right)$
O ₂	2	O ₂	1
N ₂	2 $\left(\frac{79}{21}\right)$	H ₂ O	2

The energy balance reduces to (with Q = 0): $\Delta H = 0$, or $\Delta H_{\text{products}} - \Delta H_{\text{reactants}} + \Delta H_{\text{rxn}}^{\circ} = 0$.

This solution uses the heats of combustion:

Heat of reaction

$$\begin{aligned}\Delta H_{\text{rxn}}^{\circ}(25) &= -\left[\sum \Delta H_{\text{c, products}}^{\circ} - \sum \Delta H_{\text{c, reactants}}^{\circ}\right] \\ &= -\left[\{2(-10.8) + 0\} - \{(-45.57)(1) + 0\}\right] \\ &= -[-21.6 + 45.57] = -23.97 \text{ k cal}\end{aligned}$$

Sensible heats:

$\Delta H_{\text{reactants}}$

(continued)

Solutions Chapter 26

$$\begin{array}{lcl}
 \text{N}_2: & 2 \left(\frac{79}{21} \right) (3,570 - 179) & = 25,600 \text{ k cal} \\
 \text{O}_2: & 2 (3,745 - 175) & = 7,140 \text{ k cal} \\
 \text{N}_2\text{H}_4: & 33.2 (100 - 25) & = 2.49 \text{ k cal}
 \end{array} \quad \left. \vphantom{\begin{array}{l} \text{N}_2 \\ \text{O}_2 \\ \text{N}_2\text{H}_4 \end{array}} \right\} \Sigma = 35.49 \text{ k cal}$$

$$\Delta H_{\text{Reactants}} - \Delta H_{\text{Prod}}^{\circ} (25) = 2.49 + 7,140 + 25.6 + 23.97 = 59.20 \text{ k cal}$$

Use trial and errorAssume 500°C : $\Delta H_{\text{products}}$:

$$\begin{array}{llll}
 \text{N}_2 & 8.52 (3,396) & = & 29.0 \\
 \text{O}_2 & 1 (3,570) & = & 3.57 \\
 \text{H}_2\text{O (g)} & 2 (3,448) & = & \underline{6.90} \\
 & & & 39.45 \text{ k cal}
 \end{array}$$

$$39.45 - 59.20 = -19.75$$

Assume 1000°C :

$$\begin{array}{llll}
 \text{N}_2 & 8.52 (7,308) & = & 62.30 \\
 \text{O}_2 & 1 (7,741) & = & 7.74 \\
 \text{H}_2\text{O (g)} & 2 (9,01) & = & \underline{18.02} \\
 & & & 88.06 \text{ k cal}
 \end{array}$$

$$88.06 - 59.20 = 28.86$$

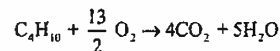
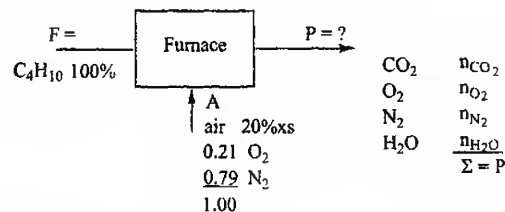
Interpolate between 500°C and 1000°C :

$$\frac{19.75}{28.86 - (-19.75)} = \frac{19.75}{48.61} = 0.406 \quad 0.406(500^{\circ}\text{C}) = 203^{\circ}\text{C}$$

$$T = 500 + 203 \approx 700^{\circ}\text{C}$$

Solutions Chapter 26

26.6

Basis: $20\text{ft}^3 \text{C}_4\text{H}_{10}$ at 15.5 psia and 70°F (1 min)

$$\begin{aligned}
 \text{C}_4\text{H}_{10} \text{ IN: } \quad n &= \frac{pV}{RT} = F = \frac{15.5 \text{ psia}}{530^{\circ}\text{R}} \left| \frac{20 \text{ ft}^3}{10.73 (\text{psia})(\text{ft}^3)} \right| \frac{1 (\text{lb mol})(^{\circ}\text{R})}{1} \\
 &= 0.0545 \text{ lb mol}
 \end{aligned}$$

Air IN:

$$\begin{array}{llll}
 \text{O}_2 \text{ reqd} & 0.0545 \left(\frac{13}{2} \right) & = & 0.354 \text{ lb mol} \\
 \text{O}_2 \text{ xs} & 0.0545 \left(\frac{13}{2} \right) (.2) & = & \underline{0.071} \\
 \text{Total O}_2 & & & 0.425 \\
 \text{N}_2 \text{ in} & 0.425 \left(\frac{.79}{.21} \right) & = & 1.599 \text{ lb mol}
 \end{array}$$

Material Balances

(continued)

Solutions Chapter 26

	in		out (lb mol)	
C:	0.0545 (4)	=	n_{CO_2}	= 0.218
N ₂ :	1.599	=	n_{N_2}	= 1.599
2H:	$0.0545 \left(\frac{10}{2} \right)$	=	$n_{\text{H}_2\text{O}}$	= 0.273
2O:	0.425	=	$n_{\text{CO}_2} + (n_{\text{H}_2\text{O}}/2) + n_{\text{O}_2}$	$n_{\text{O}_2} = 0.071$
Total moles out = 2.161 lb mol				
$V = \frac{nRT}{p} = \frac{2.161 \text{ lb mol} \left \frac{10.73(\text{psia})(\text{ft}^3)}{(\text{lb mol})(^\circ\text{R})} \right 1360^\circ\text{R}}{14.9 \text{ psia}} = 2116 \text{ ft}^3 \text{ at } 900^\circ\text{F and } 14.9 \text{ psia}$				
Reference temperature = 77°F				
$\Delta H = \Delta H_{\text{rxn}}^\circ + \Delta H_{\text{products}}^{\text{sensible}} - \Delta H_{\text{reactants}}^{\text{sensible}}$				
Per g mol of C ₄ H ₁₀				
$\Delta H_{\text{rxn}}^\circ = 5(-241.826) + 4(-393.51) - 1(-124.73) - \frac{13}{2}(0) = -2658.44 \text{ kJ/g mol}$				
On the basis of 0.0545 lb mol C ₄ H ₁₀				
$\frac{0.0545 \text{ lb mol} \left \frac{454 \text{ g}}{1 \text{ lb}} \right \frac{-2658.44 \text{ kJ}}{\text{g mol}} \left \frac{1 \text{ Btu}}{1.055 \text{ kJ}} \right }{1} = -62,349 \text{ Btu}$				
Sensible heat of entering C ₄ H ₁₀ (361 J/g mol)				
$\frac{0.0545 \text{ lb mol} \left \frac{454 \text{ g}}{1 \text{ lb}} \right \frac{0.361 \text{ kJ}}{\text{g mol}} \left \frac{1 \text{ Btu}}{1.055 \text{ kJ}} \right }{1} = 8.47 \text{ Btu}$				

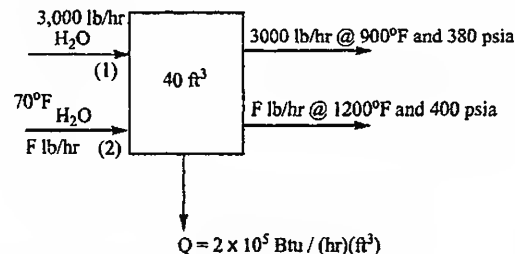
Solutions Chapter 26

Sensible heat of exiting gases

$$\begin{aligned}
 \Delta H_{\text{CO}_2} &= (0.218 \text{ lb mol})(36,953 \text{ Btu/lb mol}) = 8,056 \text{ Btu} \\
 \Delta H_{\text{N}_2} &= (1.599)(24,560) = 32,721 \\
 \Delta H_{\text{H}_2\text{O}} &= (0.273)(29,301) = 7,999 \\
 \Delta H_{\text{O}_2} &= (0.070)(25,811) = 1,833 \\
 &50,159 \text{ Btu} \\
 \Delta H &= -62,349 + 50,159 - 8.5 = -12,198 \text{ Btu}
 \end{aligned}$$

26.7

Steady state process, no reaction.



$$\text{Basis: } Q = (2 \times 10^5)(40) = 8 \times 10^6 \text{ Btu} = 1 \text{ hour}$$

The energy balance is: $Q = \Delta H$

In

	mass (lb)	$\Delta \hat{H}(\text{Btu/lb})$	$\Delta H(\text{Btu})$
(1)	3000 (satd)	38.05	1.14×10^5
(2)	F (satd)	38.05	38.05F

(continued)

Solutions Chapter 26

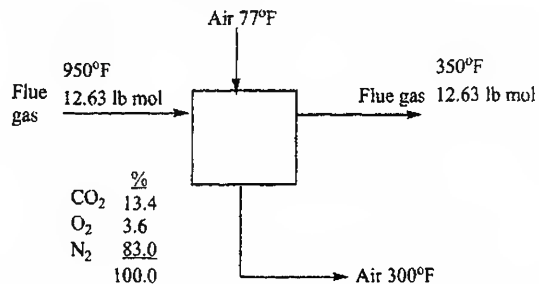
Out			
(1)	3000	1469.2	4.408×10^6
(1)	F	1628.8	1628.8F
	ΔH_{out}	ΔH_{in}	Q
$(1628.8F + 4.408 \times 10^6) - (38.05F + 1.14 \times 10^5) = 8 \times 10^6$			
$F = 2,316 \text{ lb/hr}$			

26.8

Basis: 1 hr

The number of moles of flue gas is

$$n_{fg} = \frac{(1.3 \times 10^4 \text{ ft}^3) (1 \text{ atm}) (\text{lb mol}) (^\circ \text{R})}{(1410^\circ \text{R}) (0.7302) (\text{ft}^3) (\text{atm})} = 12.63 \text{ lb mol}$$



The energy balance with $Q = 0$ reduces to $\Delta H_{out} = \Delta H_{in}$

Solutions Chapter 26

Comp.	%	lb mol	$\Delta \hat{H} (950^\circ\text{F} - 77^\circ\text{F}) \text{ Btu/lb}$	$\Delta H \text{ (Btu)}$	$\Delta \hat{H} (350^\circ\text{F} - 77^\circ\text{F}) \text{ Btu/lb}$	$\Delta H \text{ (Btu)}$
CO ₂	13.4	1.69	21,480	36,301	6,257	10,574
O ₂	3.6	0.45	15,370	6,917	4,580	2,061
N ₂	<u>83.0</u>	<u>10.48</u>	14,553	<u>152,515</u>	4,441	<u>46,542</u>
	100.10	12.63		195,733		59,177
			$\Delta \hat{H} (300^\circ\text{F} - 77^\circ\text{F}) \text{ Btu/lb}$	$\Delta H \text{ (Btu)}$		
Air	100	n	3633	3633 n		

$3663n + 59,177 = 195,733 + 0$

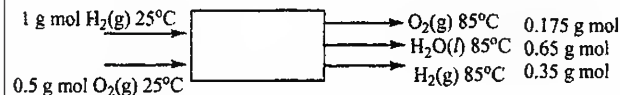
$n = 37.28 \text{ lb mol}$

$V = \frac{(37.28 \text{ lb mol})(0.7302)(\text{ft}^3)(\text{atm})(537^\circ\text{R})}{(\text{lb mol})(^\circ\text{R})(1 \text{ atm})} = \boxed{1.46 \times 10^4 \text{ ft}^3 / \text{hr}}$ at 77°F and 1 atm

26.9

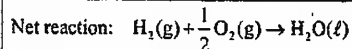
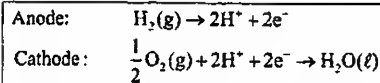
Basis: 1 g mol H₂ (g)

Assume 85°C means the exit water is at 85°C , but the H₂ and O₂ enter at 25°C for simplicity.



The overall equation for the electro chemical reaction is

(continued)



Use the CD to get ΔH for O_2 and H_2 . The energy balance reduces to $\Delta H = W$.

Enthalpy in Enthalpy out ($\Delta H = \int \text{CpdT}$)
 sensible heats: sensible heats:

ΔH of $\text{H}_2 = 0$ ΔH of $\text{H}_2\text{O}(\ell) = \frac{0.65}{(\text{gK}^\circ\text{C})} \left| \frac{4.18 \text{ J}}{\text{gK}^\circ\text{C}} \right| \frac{18 \text{ g}}{\text{g mol}} \left| \frac{(85-25)^\circ\text{C}}{\text{gK}^\circ\text{C}} \right| = 2.937 \text{ kJ}$

ΔH of $\text{O}_2 = 0$ ΔH of $\text{H}_2 = (0.35)(1.732) = 0.606$
 ΔH of $\text{O}_2 = (0.175)(1.783) = 0.312$

$\Delta \hat{H}^\circ_f$ of $\text{H}_2 = 0$

$\Delta \hat{H}^\circ_f$ of $\text{O}_2 = 0$ $\Delta \hat{H}^\circ_f(\text{kJ/g mol}) = -285.840 \text{ kJ/g mol}$

$\Delta H^\circ_{\text{rxn}} = (0.65)[(-285.840) - 0] = -185.796 \text{ kJ/g mol H}_2$

$W = \Delta H_{\text{out}} - \Delta H_{\text{in}} + \Delta H^\circ_{\text{rxn}} = (0.606 + 0.312 + 2.937) - 0 + (-185.796)$

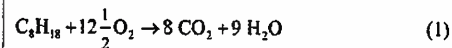
$= -181.941 \text{ kJ}$

$\frac{-181.941 \text{ kJ}}{1 \text{ kJ}} \left| \frac{2.773 \times 10^{-4} \text{ kWh}}{1 \text{ kJ}} \right| = \boxed{0.0505 \text{ kWh}}$

26.10

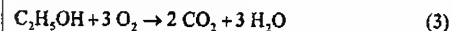
The chemical formulas and combustion analyses are as follows:

Combustion of iso-octane:



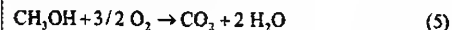
$\text{lb} = 114 + 400 = 514 \rightarrow 352 + 162 = 514$ (2)

Combustion of ethyl alcohol:



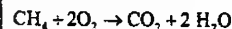
$\text{lb} = 46 + 96 = 142 \rightarrow 88 + 54 = 142$ (4)

Combustion of methyl alcohol



$\text{lb} = 32 + 48 = 80 \rightarrow 44 + 36 = 80$ (6)

Combustion of methane:



$\text{lb} = 16 + 32 = 80 \rightarrow 44 + 36 = 80$

Results

	Mol. wt.	lb per gal	Heat of Combustion (Btu)	
			per lb mol	per gal
Iso-Octane	114	5.793	2,173,000	110,423
Ethyl Alcohol	46	6.630	533,000	76,822
Methyl Alcohol	32	6.610	269,000	55,565
MTBE	88	6.2	1,328,800	93,620
CNG*	16	2.5*	341,000	53,280

*Effective density. Compressed natural gas dissolved in a suitable liquid.

(continued)

Solutions Chapter 26

	mpg Relative to iC ₈	mpg* mpg	lb of CO ₂ Exhausted					Ratio to iC ₈
			Consumed gal/1000 miles	per lb mol	per gal	% Less than iC ₈	lb CO ₂ Emitted 1000 miles	
Iso-Octane	100.00	40.00	25.00	352	17.887	0	447.175	1.00000
Ethyl Alcohol	69.6	27.83	35.93	88	12.680	29.07	445.592	1.01882
Methyl Alcohol	50.0	20.13	49.68	44	9.089	49.28	451.529	1.00974
MTBE	84.4	33.91	29.49	220	15.500	13.36	457.095	1.02218
CNG	48.4	19.52	51.23	44	6.875	61.56	352.206	0.78762

* Proportional to heat of combustion/gal.

26.11

Basis: 1 min

Find the lb mol/hr (assume waste gas MW = 29, otherwise the composition has to be known).

$$n_{in} = \frac{(5000 \text{ ft}^3)(1 \text{ atm})(\text{lb mol})/(\text{°R})}{(590 \text{ °R})(0.7302)(\text{ft}^3)(\text{atm})} = 11.61 \text{ lb mol}$$

HHV is at SC so assume the CH₄ enters at SC

$$\text{HHV} = \frac{359 \text{ ft}^3}{\text{lb mol}} \left| \frac{1059 \text{ Btu}}{1 \text{ ft}^3} \right| = 3.80 \times 10^5 \text{ Btu / lb mol CH}_4$$

$$\Delta H_{rxn}(77^\circ \text{F}) = -3.80 \times 10^5 \text{ Btu / lb mol CH}_4$$

The energy balance reduces to $\Delta H + \Delta H_{rxn} = 0$. Assume C_p of the incinerated exhaust gas is that of air. Let n_{CH_4} be the lb mol CH₄ in.

ΔH OUT at 1200° F

Solutions Chapter 26

Assume the exhaust gas has the same properties as air, or else the composition has to be known; $\Delta \hat{H}$ data are from the CD.

$$\Delta H_{77^\circ \text{F}}^{1200^\circ \text{F}} = \frac{(n_{in} + n_{CH_4})}{\text{g mol}} \left| \frac{19,132 \text{ J}}{\text{g mol}} \right| \left| \frac{454 \text{ g}}{1 \text{ lb}} \right| \left| \frac{1 \text{ Btu}}{1,055 \text{ J}} \right| = (n_{CH_4} + 11.61)(8233) \text{ Btu}$$

ΔH IN at 130° F

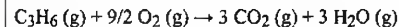
$$\Delta H_{77^\circ \text{F}}^{130^\circ \text{F}} = (11.61)(857)(45.4) / 1,055 = 4282 \text{ Btu}$$

$$8233n_{CH_4} + 95,586 - 4,282 + n_{CH_4}(-3.802 \times 10^5) = 0$$

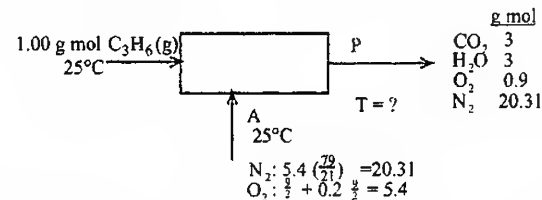
$$n_{CH_4} = 0.25 \text{ lb mol}$$

The ft³ at SC of CH₄ is 90 / min

26.12



Basis: 1 g mol C₃H₆(g)



$$\Delta E = 0 = -\Delta H + Q + W \quad \text{or} \quad \Delta H = \sum \Delta H_{\text{prod}} - \sum \Delta H_{\text{react}} = 0$$

(continued)

Air in: req'd O₂: 9/2 g mol

xs 20% (2) (9/2) = .9 g mol

5.4 mol O₂N₂ in 5.4 (79/21) = 20.31 g mol

Reactants	g mol	Sensible heat $\Delta\hat{H}(\text{kJ/g mol})$	$\Delta\hat{H}_f^\circ(\text{kJ/g mol})$	$\Delta H(\text{kJ})$
C ₃ H ₈ (g)	1	0	20.41	20.41
O ₂ (g)	5.4	0	0	0
N ₂ (g)	20.31	0	0	0
				20.41

Products: Assume T = 2000K

	g mol	$\Delta\hat{H}(\text{kJ/g mol})$	$\Delta\hat{H}_f^\circ(\text{kJ/g mol})$	$\Delta H(\text{kJ})$
CO ₂ (g)	3	(92.466-.912)	-393.51	-905.87
H ₂ O(g)	3	(73.136-.837)	-241.826	-508.58
O ₂ (g)	0.9	(59.914-.732)	0	53.26
N ₂ (g)	20.31	(56.902-.728)	0	1140.89
				-220.30

Assume T = 2500K

CO ₂ (g)	3	(123.176-.912)	-393.51	-813.74
H ₂ O(g)	3	(98.867-.837)	-241.826	-431.39
O ₂ (g)	0.9	(79.119-.732)	0	70.55
N ₂ (g)	20.31	(75.060-.728)	0	1509.68
				-335.11

By linear interpolation $T = 2180\text{K}$ Calculation T = 2250K, gives better precision $T = 2217\text{K}$

26.13

By making an adiabatic flame temperature calculation for each gas, the values, in order of increasing temperature, are found to be:

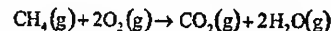
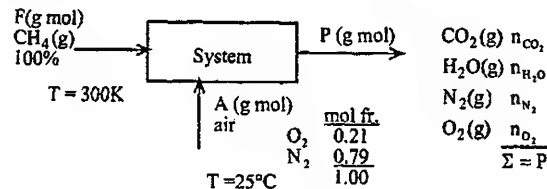
CH₄ (3750°F)C₂H₆ (3820°F)C₄H₈ (3870°F)

Equilibrium aspects were not taken into account in the calculations. However, you can obtain the same relationships (but not the values of T) by looking at the values of $\Delta\hat{H}_{\text{rxn}}^\circ$.

26.14

Steps 1, 2, 3, and 4:

This is an open system with reaction. The process is in the steady state.



$\Delta\hat{H}_f^\circ(\text{kJ/g mol})$	-74.84	0	-393.51	-241.826
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(continued)

Solutions Chapter 26

Step 5: Basis: 1 g mol $\text{CH}_4(\text{g})$

Step 4: Calculate the amount of entering air:

O_2 required: 2 g mol

O_2 entering: $2(1.10) = 2.20$ g mol

N_2 entering: $2.20 (0.79/0.21) = 8.28$ g mol

Steps 5, 6, 7, 8, and 9

Calculate the amount of exit gas

Balances (g mol)	In		Out
C	1	=	n_{CO_2}
H	1(4)	=	$n_{\text{H}_2\text{O}}(2)$
O	2.20(2)	=	$n_{\text{O}_2}(2) + n_{\text{H}_2\text{O}} + n_{\text{CO}_2}(2)$
N	8.28	=	n_{N_2}

Summary of moles out:

$n_{\text{CO}_2} = 1$ g mol $n_{\text{N}_2} = 8.28$ g mol

$n_{\text{H}_2\text{O}} = 2$ g mol $n_{\text{O}_2} = 0.20$ g mol

The energy balance for an adiabatic process reduces to $\Delta H = 0 = \sum_{\text{products}} n_i \Delta \hat{H}_i - \sum_{\text{reactants}} n_i \Delta \hat{H}_i$. Because the outlet temperature is to be calculated, if we use enthalpy tables for the gases, a trial and error solution is required. If we integrate heat capacity equations, solution of a cubic or quadratic equation in the outlet temperature is required (if truncate C_p equations).

Compound	g mol	T	$\Delta \hat{H}_i^\circ$ (kJ/g mol)	$\Delta \hat{H}_{i,298}^\circ$ (kJ/g mol)	ΔH (kJ)
Reactants					

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$\text{CH}_4(\text{g})$	1.0	300K	-74.84	(0.950-0.879)	-74.77
$\text{O}_2(\text{g})$	2.2	25°C	0	0	0
$\text{N}_2(\text{g})$	8.28	25°C	0	0	0
					-74.77

Products:

Assume $T = 2000\text{K}$

$\text{CO}_2(\text{g})$	1.0	2000K	-393.51	(92.446-0.912)	-301.98
$\text{H}_2\text{O}(\text{g})$	2.0	2000K	-241.826	(73.136-0.837)	-339.05
$\text{O}_2(\text{g})$	0.20	2000K	0	(59.914-0.732)	11.84
$\text{N}_2(\text{g})$	8.28	2000K	0	(56.902-0.728)	465.12
					-164.07

$T = 2000\text{K}$ is too low

Assume $T = 2250\text{K}$

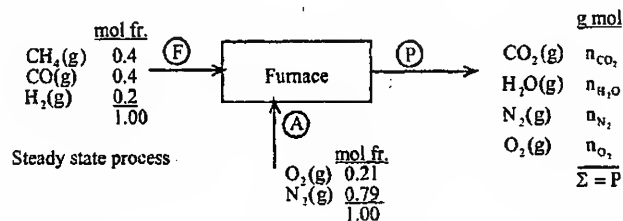
$\text{CO}_2(\text{g})$	1.0	2250K	-393.51	(107.738-0.912)	-268.68
$\text{H}_2\text{O}(\text{g})$	2.0	2250K	-241.826	(85.855-0.837)	-313.62
$\text{O}_2(\text{g})$	0.20	2250K	0	(69.454-0.732)	13.74
$\text{N}_2(\text{g})$	8.28	2250K	0	(65.981-0.728)	540.30
					-28.26

$T = 2250\text{K}$ is too high

A linear interpolation gives

$$T = 2250 - \frac{-74.77 - 28.26}{-164.07 - 28.26} (250) = \boxed{2158}$$

26.15



Basis: 1 g mol F

Calculation for xs air:

	<u>O₂ req</u>	<u>g mol</u>
$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$	$0.4(2)$	$= 0.8$
$\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2$	$0.4(\frac{1}{2})$	$= 0.2$
$\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O}$	$0.2(\frac{1}{2})$	$= 0.1$
xs O ₂ :	$1.1(3.0)$	3.3
	Total O ₂ in	4.4
N ₂ in:	$4.4(\frac{79}{21})$	$= 16.55$

Material balance for output (g mol)

		<u>g mol</u>
CO ₂ : (C balance)	$0.4 + 0.4 =$	0.80
H ₂ O: (H ₂ bal)	$0.4(2) + 0.2 =$	1.0
O ₂ : (O ₂ bal)	$0.4(\frac{1}{2}) + 4.4 - 0.80 - 1.0(\frac{1}{2}) =$	3.3 (the xs)

N₂

16.55

Energy balance reduces to $Q = \Delta H$ and $Q = 0$ so $\Delta H = 0$ Let $T_{\text{ref}} = 25^\circ\text{C}$ Let $T = 1000^\circ\text{C}$

<u>Output</u>	<u>g mol</u>	<u>$\Delta \hat{H}_f^\circ$ (cal/g mol)</u>	<u>$\Delta \hat{H}_{25}^\circ$ (cal/g mol)</u>	<u>ΔH (cal)</u>
CO ₂ (g)	0.8	-94,052	(11,846-217.9)	-65,939
H ₂ O(g)	1.0	-57,798	(9210-200.3)	-48,788
O ₂ (g)	16.55	0	(7482-174)	+120,947
N ₂ (g)	3.3	0	(7916-175)	+25,545
Total				+31,765

Input (stays same for each output T)

CH ₄ (g)	0.4	-17,889	0	-7,155.6
CO(g)	0.4	-26,416	0	-10,566.4
H ₂ (g)	0.2	0	0	
O ₂ (g)	4.4	0	0	
N ₂ (g)	16.55	0	0	
Total				-17,722

$$\Delta H = 31,765 - (-17,722) = 49,487 \text{ (too high)}$$

Let $T = 500^\circ\text{C}$

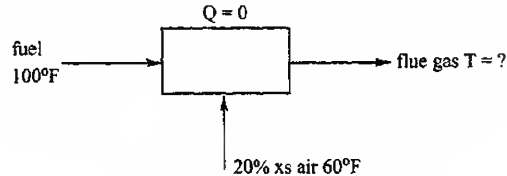
<u>Output</u>	<u>g mol</u>	<u>$\Delta \hat{H}_f^\circ$ (cal/g mol)</u>	<u>$\Delta \hat{H}_{25}^\circ$ (cal/g mol)</u>	<u>ΔH (cal)</u>
CO ₂ (g)	0.8	-94,052	(5340-217.9)	-71,144
H ₂ O(g)	1.0	-57,798	(4254-200.3)	-53,744
N ₂ (g)	16.55	0	(3569-174)	+56,187
O ₂ (g)	3.2	0	(3745-175)	+11,781
Total				-56,920

$$\Delta H = 56,920 - (-56,920) = 113,840 \text{ (too low)}$$

(continued)

$$1000^{\circ}\text{C} - \frac{49,487 - 0}{49,487 - (-39,698)} (500) = \boxed{723^{\circ}\text{C}}$$

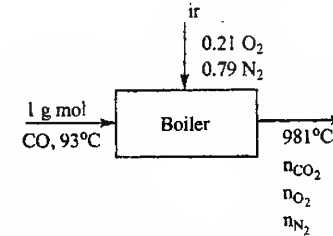
26.16

No W , ΔPE , ΔKE , Q so $\Delta H = 0$

$$\Delta H = \Delta H_{\text{Prod}} + \Delta H^{\circ}_{\text{Rxn}} - \Delta H_{\text{React}} = 0 \quad \text{so that} \quad \Delta H_{\text{Prod}} = \Delta H_{\text{React}} - \Delta H^{\circ}_{\text{Rxn}}$$

- (1) increase the inlet temperature of the fuel (increase ΔH of reactants)
- (2) increase the inlet temperature of the air (increase ΔH of reactants)
- (3) reduce the excess air (relative to the fuel!) but still have complete combustion (the number of moles of N_2 , O_2 are reduced), and use less energy to go from 77°F to the adiabatic reaction temperature)
- (4) increase the concentration of CH_4 in the gas
- (5) use oxygen enriched air

26.17

Basis: 1 g mol CO; assume complete combustion because of the excess O_2 

$$\text{O}_2 \text{ Required: } \frac{1 \text{ g mol CO}}{1} \times \frac{0.5 \text{ mol O}_2}{1 \text{ mol CO}} = 0.5 \text{ mol O}_2$$

Excess O_2 : $(1+x)0.5 = \text{mols O}_2 \text{ in feed}$

where $x = \text{fraction excess O}_2$

Material Balance:

Component	mols in	mols out
C	1	$n_{\text{CO}_2} = 1$
O_2	$0.5(1+x)$	$n_{\text{O}_2} = 0.5x$
N_2	$0.5(1+x)(0.79/0.21)$	$n_{\text{N}_2} = 1.88(1+x)$

Enthalpy Balance: (Using 25°C as the reference temperature)Assume that Q is essentially zero. Then

(continued)

$$\Delta H_{\text{System}} = 0$$

$$\Delta H_{\text{Out}} - \Delta H_{\text{In}} = 0$$

$$\Delta H_{\text{In}} = \sum \Delta H_f^\circ + \sum \int_{\text{Ref}}^T C_p dT$$

$$\Delta H_{\text{In}} = 1.0(\Delta H_{f,\text{CO}}^\circ) + 1.0(\Delta H_{\text{CO},93^\circ\text{C}} - \Delta H_{\text{CO},25^\circ\text{C}}) + (1 + 0.5x)(\Delta H_{\text{O}_2,93^\circ\text{C}} - \Delta H_{\text{O}_2,25^\circ\text{C}}) +$$

$$1.88(1+x)(\Delta H_{\text{N}_2,93^\circ\text{C}} - \Delta H_{\text{N}_2,25^\circ\text{C}})$$

$$\Delta H_{\text{In}} = 1.0(-110520) + 1.0(2708.58 - 728) + (1 + 0.5x)(2744.92 - 732) +$$

$$(1.88(1+x)(2705.94 - 728))$$

$$\Delta H_{\text{In}} = -102807.97 + 4724.99x \text{ J/mol}$$

$$\Delta H_{\text{Out}} = \sum \Delta H_f^\circ + \sum \int_{\text{Ref}}^T C_p dT$$

$$\Delta H_{\text{Out}} = 1.0(\Delta H_{f,\text{CO}_2}^\circ) + 1.0(\Delta H_{\text{CO}_2,981^\circ\text{C}} - \Delta H_{\text{CO}_2,25^\circ\text{C}}) + 0.5x(\Delta H_{\text{O}_2,981^\circ\text{C}} - \Delta H_{\text{O}_2,25^\circ\text{C}}) +$$

$$1.88(1+x)(\Delta H_{\text{N}_2,981^\circ\text{C}} - \Delta H_{\text{N}_2,25^\circ\text{C}})$$

$$\Delta H_{\text{Out}} = 1.0(-393510) + 1.0(48474.44 - 912) + 0.5x(32428.44 - 732) +$$

$$(1.88(1+x)(30653.38 - 728))$$

$$\Delta H_{\text{Out}} = -289687.85 + 72107.93x \text{ J/mol}$$

$$\Delta H_{\text{Out}} - \Delta H_{\text{In}} = 0 = -289687.86 + 72107.93x - (-102807.97 + 4724.99x)$$

$$\text{Solve for } x: \quad x = 2.76$$

$$\text{Percent Excess Air} = 276\%$$

26.18

a. Gas Basis 100 g mol Ref. temp. 25°CMaterial balances:Products

Comp.	%mol	O ₂ reqd.	mol	CO ₂	H ₂ O	N ₂
CH ₄	96.0	CH ₄ + 2 O ₂ → CO ₂ + 2 H ₂ O (g)	192	96	192	-
CO ₂	3.0			3		
N ₂	<u>1.0</u>					1
	100.0					
N ₂ entering	192 (72/21) = 722.3					<u>722.3</u>
Total				99	192	723.4

$$Q = \Delta H = \sum \Delta H_{\text{prod}} - \sum \Delta H_{\text{react}} = 0 \text{ and solve for products}$$

$$\Delta \hat{H}_f^\circ = \begin{matrix} \text{H}_2\text{O} & \text{CO}_2 & \text{CH}_4 \\ (-241.826) & (-393.51) & (-74.84) \end{matrix}$$

In:

Comp.	g mol	$\Delta \hat{H}$ (kJ/g mol)	ΔH_f° (kJ/g mol)	ΔH (kJ)
O ₂	192.0	-(.732-.527)	0	- 39.36
CH ₄	96.0	-(.879-.630)	-74.84	-7208.54
CO ₂	3.0	-(.912-.655)	-393.51	-1181.32
N ₂	<u>1.0</u>	-(.728-.524)	0	- <u>0.20</u>
	292.0			-8429.42

Out

Use either the enthalpy tables and trial and error, or calculate the temperature so that $\Delta H_{\text{out}} = -8429.42$:

$$En_i \left[\int_{25^\circ\text{C}}^{T_c} C_{p,i} dT + \Delta \hat{H}_{f,i}^\circ \right]$$

(continued)

Solutions Chapter 26

and solve the polynomial equation obtained by integration via a computer code. The following is trial and error.

Assume $T = 2250$ K

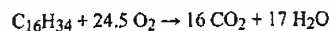
Comp.	g mol	$\Delta \hat{H}$ (kJ/g mol)	ΔH°_f (kJ/g mol)	ΔH (kJ)
CO ₂	99.0	(107.738-.912)	-393.51	-28,381.72
H ₂ O	192.0	(85.855-.837)	-241.83	-30,107.90
N ₂	723.4	(65.981-.728)	0	-47,204.02
				<u>-11,285.60</u>

Assume $T = 2500$ K

CO ₂	99.0	(123.176-.912)	-393.51	-26,853.35
H ₂ O	192.0	(98.867-.837)	-241.83	-27,608.60
N ₂	723.4	(75.060-.728)	0	-53,742.04
				<u>-720.92</u>

$$T = \frac{(-11,285) - (-8429)}{(-11,285) - (-721)}(250) + 2250 = \boxed{2318\text{K}}$$

b. Oil Basis: 100 g oil $\equiv$ 0.438 g mol C₁₆H₃₄ (mol wt = 226.27)



Ignore the ΔH of the oil and S.

In:		Out:	
	g mol		g mol
O ₂ req'd	10.75	CO ₂	7.008
N ₂ in	40.36	H ₂ O	7.446

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SO ₂	0.031
N ₂	40.36

ΔH :

Comp.	g mol	$\Delta \hat{H}$ (kJ/g mol)	ΔH°_f (kJ/g mol)	ΔH (kJ)
C ₁₆ H ₃₄	0.438	-	?	
S	0.031	-	0	
O ₂	10.75	(.527 - .732)	0	
N ₂	40.36	(.524 - .728)	0	

$\Delta H_{\text{combustion}}$ from Perry (for gaseous products) of the oil is -10,505.6 cal/g.

$$\Delta H^\circ_{\text{rxn}} = \frac{99 \text{ g}}{\text{g}} \left| \frac{-10,505.6 \text{ cal}}{\text{g}} \right| \frac{4.184 \text{ J}}{1 \text{ cal}} = -4351.59 \text{ kJ}$$

$$\Delta H^\circ_{\text{mn}} \text{ for S} = \frac{-296.90 \text{ kJ}}{\text{g mol}} \left| \frac{0.031 \text{ g mol}}{\text{g mol}} \right| = -9.20 \text{ kJ}$$

$$\Delta H_{\text{prod}} = -4371.23 \text{ kJ}$$

Assume $T = 2250$ K

Comp.	g mol	$\Delta \hat{H}$ (kJ/g mol)	ΔH°_f (kJ/g mol)	ΔH (kJ)
CO ₂	7.008	(107.738-.912)	-393.51	-2009.08
H ₂ O	7.446	(85.855-.837)	-241.826	-1167.59
SO ₂	0.031	(105.562-.984)	-296.90	<u>2633.61</u>
N ₂	40.36	(65.981-.728)	0	-543.06

Assume $T = 2500$ K

CO ₂	7.008	(123.176-.912)	-393.51	-1900.89
H ₂ O	7.446	(98.867-.837)	-241.826	-1070.71
SO ₂	0.031	(119.871-.984)	-296.90	-5.52
N ₂	40.36	(75.060-.728)	0	<u>3000.04</u>
				22.92

$$T = \boxed{2395 \text{ K}}$$

(continued)

Solutions Chapter 26

c. Coke Basis: 100 g

In: C = 95 g ash = 5 g

= 7.917 g mol

C + O₂ → CO₂

Out:

O₂ req'd = 7.917 g mol

CO₂ = 7.907 g mol

N₂ = 29.782 g mol

N₂ = 29.782 g mol

In:

ΔH_{react}

Comp.	g or mol	C _p or ΔH (kJ)	ΔT	ΔH (kJ)	$\Delta \hat{H}^\circ_f$
C	7.917	11 (J/(g mol) (K))	-7	-0.6096	0
ash	5 g	1.15 (J/(g) (°C))	-7	-0.040	?
O ₂	7.917	(.527-.732)		-1.623	0
N ₂	29.782	(.524-.728)		-6.075	0
	Total			-8.348	0

Out:

Assume T = 2250 K

Comp.	mol	ΔH (kJ/g mol)	$\Delta \hat{H}^\circ_f$	ΔH (kJ)
CO ₂	7.917	(107.738-.912)	-393.51	-2269.68
N ₂	29.782	(65.981-.728)	0	1943.36
ash	5 g	C _p ΔT = 1.15 (527-25)	?	2.80
	Total			-323.51

Assume T = 2500 K

CO ₂	7.917	(123.176-.912)	-393.51	-2147.45
N ₂	29.782	(75.060-.728)	0	2213.76
ash	5 g	C _p ΔT = 1.15 (527-298)	?	2.80
	Total			69.10

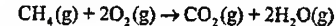
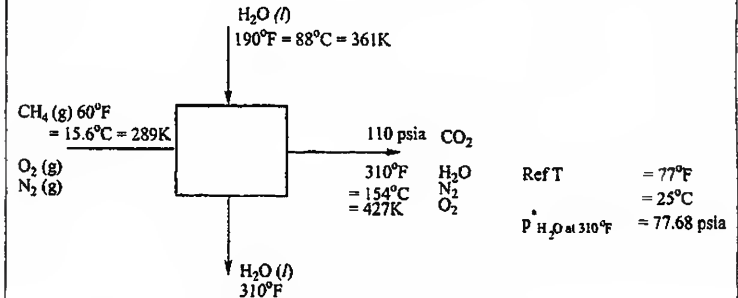
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The heat of formation of ash is not known but the contribution to ΔH will cancel in the calculations

$$T = \boxed{2445 \text{ K}}$$

The coke gives the highest temperature.

26.19



$\Delta \hat{H}^\circ_f$ kJ/g mol	-74.84	0	-393.51	-241.826
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Material Balance: Basis: 1 g mol CH₄ (= 16 g CH₄)

(continued)

Solutions Chapter 26

IN			OUT			
CH ₄	O ₂ Req'd.	N ₂	CO ₂	H ₂ O	N ₂	O ₂
1			1			
	2					
	xs = 2(0.05) = 0.1					
	2.1					0.1
		2.1				
		$\left(\frac{79}{21}\right) = 7.9$				
				2	7.9	

9 mol
dry fg

Flow process, steady state, no Q, W, ΔPE, ΔKE

$$\Delta H = 0$$

$$\Delta H_{\text{Products}} + \Delta H^{\circ}_{\text{Rxn}} = \Delta H_{\text{Reactants}}$$

(include the liquid water in the products and reactants)

Let W = g mol liquid H₂O at 310°F

$$\Delta H^{\circ}_{\text{Rxn}}$$

$$\Delta \hat{H}^{\circ}_{\text{Rxn}} = [(2)(-241.826) + (1)(-393.51)] - [0 + (1)(-74.84)]$$

$$= -877.162 + 74.84 = -802.322 \text{ kJ/g mol CH}_4$$

$$\Delta H_{\text{Products}}$$

	$\Delta \hat{H}(\text{J/g mol})$	<u>g mol</u>	<u>ΔH (J)</u>
CO ₂ (g)	(6064-912)	1	5152
N ₂ (g)	(4491-728)	7.9	27,728
O ₂ (g)	(4578-732)	0.1	385
H ₂ O(g) satd	(5220 - 837)	21.63	94,804

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$$\text{H}_2\text{O(l)}@310^\circ\text{F} \quad \left[(279.92 - 45) \frac{\text{Btu}}{\text{lb}} \right] \quad W \quad \underline{9826 \text{ W}}$$

$$\Delta H_{\text{H}_2\text{O(l)}} \text{ at } 77^\circ\text{F} = \frac{1 \text{ Btu}}{(\text{lb})(^\circ\text{F})} (77 - 32) = 45 \text{ Btu/lb}$$

$$\frac{18 \text{ lb}}{1 \text{ lb mol}} \left| \frac{1055 \text{ J}}{\text{Btu}} \right| \frac{1 \text{ lb mol}}{454 \text{ g mol}} \quad \text{Total} = 128,077 + 9826 \text{ W}$$

NOTE: $\frac{n_{\text{H}_2\text{O(g)}}}{n_{\text{dry fg}}} = \frac{p_{\text{H}_2\text{O}}}{p_T - p_{\text{H}_2\text{O}}} = \frac{77.68}{110 - 77.68} = 2.40$ hence $n_{\text{H}_2\text{O(g)}} = 9(2.40) = 21.63$

$\Delta H_{\text{Reactants}}$	$\Delta \hat{H}(\text{J/g mol})$	<u>g mol</u>	<u>ΔH (J)</u>
CH ₄ (g)	(561 - 879)	1	-318
O ₂ (g)	(468 - 732)	2.1	-544
N ₂ (g)	(466 - 728)	7.9	-2070
H ₂ O (l)	$(157.95) - 45 \left(\frac{18}{454} \right) (1055)$	$(W + 21.63 - 2)$	$4724.5 W + 92742$

$$128,077 + 9826W + (-802,322) = -2942 + 4724.5 W + 92742 \quad W = 149.8$$

$$(149.8) (18/16) = \boxed{168.5 \text{ lb H}_2\text{O/lb CH}_4}$$

26.20

Assumptions

- The tank is adiabatic for the short period of time involved.
- Both the reactants and products are ideal gases.
- There is no work.
- Combustion is complete.

(continued)

5. Unsteady state process.

6. Closed system.

The reaction is $\text{H}_2(\text{g}) + \frac{1}{2}\text{O}_2(\text{g}) \rightarrow \text{H}_2\text{O}(\text{g})$

The energy balance reduces to

$$\Delta U = 0 = \Delta H - \Delta(pV)$$

$$\Delta U = \Delta H_{\text{Prod}} - \Delta H_{\text{React}} + \Delta H^{\circ}_{\text{rxn}}(25^{\circ}\text{C}) - V\Delta p = 0$$

The final temperature comes from the value of ΔU .Basis: 1 g mol of H_2 Reference temperature: 25°C $\Delta H_{\text{Rxn}}(25^{\circ}\text{C})$

$$\Delta H_{\text{rxn}}(25^{\circ}\text{C}) = \sum_{\text{products}} n_i \Delta \hat{H}^{\circ}_{\text{fi}} - \sum_{\text{reactants}} n_i \Delta \hat{H}^{\circ}_{\text{fi}}$$

$$= (1)(-241,820) - \left(\frac{1}{2}\right)0 - (1)0 = -241,820 \text{ kJ/g mol H}_2$$

 $\Delta H_{\text{React}}(25^{\circ}\text{C})$ All values are zero because $\Delta T = 0$ from the reference T.Calculate ΔH of the products at TIf you integrate the heat capacity equations to get ΔH_{Prod} , you will have to solve acubic or quadratic equation (if you truncate the equation) in T. Alternately you can use the tables for the combustion gases in the Appendix. Don't forget to subtract $\Delta H(25^{\circ}\text{C})$ because the reference T for the tables is 0°C .If the gas is ideal, $\Delta(pV) = R\Delta(nT)$. Note that $n_1 = 3.38 \text{ g mol}$ and $n_2 = 2.88 \text{ g mol}$, and T_{final} is the single unknown.

$$\Delta(pV) = \frac{8.314 \text{ J}}{(\text{g mol})(\text{K})} [(2.88 \text{ g mol})(T \text{ in K}) - 3.38(298)]$$

$$= 23.94T - 8374 \text{ in J}$$

$$\Delta H_{\text{Prod}} - \Delta(pV) = 241.820$$

Comp.	g mol	$\Delta \hat{H}(\text{kJ/g mol}); T_{\text{ref}} = 298$		$\Delta H(\text{kJ})$	
		<u>3000K</u>	<u>3500K</u>	<u>3000K</u>	<u>3500K</u>
$\text{H}_2\text{O}(\text{g})$	1	124.683	151.963	124.683	151.963
$\text{N}_2(\text{g})$	1.88	92.784	111.403	174.434	209.438
$-\Delta(pV)$				<u>-63.446</u>	<u>-83.782</u>
Total				235.67	277.62

Linear interpolation to 241.820 gives $T \approx \boxed{3045\text{K}}$ Assume ideal gas at 25°C and 1 atm. Then the tank volume is

$$\frac{3.38 \text{ g mol}}{1000 \text{ g}} \left| \frac{1 \text{ kg}}{\text{g mol}} \right| \frac{22.415 \text{ L}}{\text{g mol}} = 0.0758 \text{ L}$$

To avoid calculating z , assume ideal gas at final conditions (otherwise use Kay's method). The final pressure is

$$p = \frac{nRT}{V} = \frac{2.88 \times 10^{-3} \text{ g mol}}{(\text{g mol})(\text{K})} \left| \frac{0.08206(\text{L})(\text{atm})}{\text{g mol}} \right| \frac{3045 \text{ K}}{0.0758 \text{ L}} \left| \frac{101.3 \text{ kPa}}{1 \text{ atm}} \right| = 962 \text{ kPa}$$

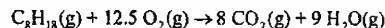
This pressure probably does not exceed the specifications for the tank.

26.21

Assumptions

- (1) The reactants and products are ideal gases
- (2) Combustion is complete
- (3) The process is unsteady state, closed system

The reaction is



The energy balance reduces to

$$\Delta U = Q + W \quad \text{or} \quad Q = \Delta U - W$$

$$\text{Let } \Delta U \equiv \Delta H_{\text{Prod}} - \Delta H_{\text{React}} + \Delta H_{\text{rxn}}(25^\circ\text{C})$$

If you want to calculate $\Delta \hat{U}_r^0$ for each compound,

$\Delta \hat{U}_r^0 = \Delta \hat{H}_r^0 - \Delta(p\hat{V})^0 = \Delta \hat{H}_r^0 - R(298)(\Delta n)$ for an ideal gas. For C_8H_{18} , the correction is + 19.8 J/g mol and for H_2O the correction is + 1.24 J/g mol.

Number of initial moles

$$n_{\text{initial}} = \frac{(300 \text{ kPa})(0.8 \text{ m}^3)(\text{kg mol})(\text{K})}{(8.314 \text{ kPa})(\text{m}^3)(298 \text{ K})} = 0.0969 \text{ kg mol} \quad \text{or } 96.9 \text{ g mol}$$

Let $x = \text{mol of C}_8\text{H}_{18}$. Then $x + 12.5x + 12.5x (79/21) = 96.9$; $x = 1.602$ Initial component g mol

C_8H_{18}	1.602
O_2	20.0
N_2	75.3

Final component g mol

0
0
75.3

CO_2	0	12.82
H_2O	0	14.42
	96.9	102.5

Basis: 1.602 g mol C_8H_{18} (g) $\Delta H_{\text{rxn}}(25^\circ\text{C})$

$$\begin{aligned} \Delta H_{\text{rxn}}(25^\circ\text{C}) &= \sum_{\text{products}} n_i \Delta \hat{H}_{i,r}^0 - \sum_{\text{reactants}} n_i \Delta \hat{H}_{i,r}^0 \\ &= (12.8)(-393.520) + (14.4)(-241.820) - (1.602)(-208.450) = -8,185 \text{ kJ} \end{aligned}$$

 $\Delta H_{\text{React}}(25^\circ\text{C})$ $\Delta H_{\text{React}}(25^\circ\text{C}) = 0$ because the reactants are at the reference temperature. $\Delta H_{\text{Prod}}(1000 \text{ K})$ Data from the tables in Appendix D6. Or use the integration of the heat capacity equations or the CD.

Comp.	g mol	$\Delta \hat{H}(1000\text{K} - 298\text{K}) \text{ kJ/g mol}$	$\Delta H \text{ (kJ)}$
$\text{N}_2(\text{g})$	75.3	21.443	1,615
$\text{H}_2\text{O}(\text{g})$	14.4	25.986	374
$\text{CO}_2(\text{g})$	12.8	33.396	427
Total	102.5		2,416

The final volume is

$$V = \frac{nRT}{p} = \frac{(0.1025)(8.314)(1000)}{300} = 2.841 \text{ m}^3/\text{kg mol}$$

(2.841 L/g mol)

Work against the atmosphere on expansion

(continued)

$$W = -\int p dV = -p\Delta V = -\Delta pV = -R\Delta(nT)$$

$$= - [8.314 \text{ J / (g mol) (K)}] [(102.5)(1000) - (96.9)(298)] (\text{g mol) (K)}$$

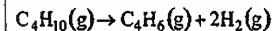
$$= -612.11 \times 10^3 \text{ J or } -612.11 \text{ kJ}$$

$$Q = [2,416 - 0 + (-8,185)] - [-612] = \boxed{-5,157 \text{ kJ}}$$

26.22

Open process, steady state

$$Q = \Delta H = \Delta H_{\text{exh}} - \Delta H_{\text{enter}} + \Delta H_{\text{rxn}}^{\circ}$$



Basis: 1 g mol butane gas

$$Q = \Delta H_{\text{Prod.}} - \Delta H_{\text{React.}} + \Delta H_{\text{rxn}}(25^{\circ}\text{C})$$

$$\Delta \hat{H}_f^{\circ}(\text{C}_4\text{H}_6)_{\text{gas}} = -165.5 \text{ kJ/g mol } (-162.2 \text{ from the CD})$$

$$\Delta \hat{H}_f^{\circ}(\text{C}_4\text{H}_{10})_{\text{gas}} = -124.73 \text{ kJ / g mol}$$

$$\Delta H_{\text{rxn}}^{\circ} = (1)(-165.5) + (2)(0) - (1)(-124.73) = -40.77 \text{ kJ}$$

$$\text{Sensible heats: } T = 1000\text{K} \quad T_{\text{ref}} = 25^{\circ}\text{C} (298\text{K})$$

$$\Delta H = \int_{298}^{1000} C_p dT$$

$$C_p = a + bT + cT^2 + dT^3$$

$$\therefore \Delta H = aT + \frac{b}{2}T^2 + \frac{c}{3}T^3 + \frac{d}{4}T^4$$

$$\Delta \hat{H}_{\text{C}_4\text{H}_6} = 11.92T + 1.346 \times 10^{-1}T^2 - 4.767 \times 10^{-5}T^3 + 7.368 \times 10^{-9}T^4 \Big|_{298}^{1000}$$

$$\Delta \hat{H}_{\text{C}_4\text{H}_6} = 91.92 \text{ kJ / g mol}$$

$$\Delta \hat{H}_{\text{C}_4\text{H}_{10}} = 92.3T + 1.394 \times 10^{-1}T^2 - 5.157 \times 10^{-5}T^3 + 8.745 \times 10^{-9}T^4 \Big|_{25}^{727}$$

(continued)

Solutions Chapter 26

$$\Delta \hat{H}_{C_4H_6} = 121.0 \text{ kJ/g mol}$$

$$\Delta \hat{H}_{H_2} = 28.84T + 3.825 \times 10^{-5}T^2 + 1.096 \times 10^{-6}T^3 - 2.175 \times 10^{-10}T^4 \left|_{25}^{727}\right.$$

$$\Delta \hat{H}_{H_2} = 20.63 \text{ kJ/g mol}$$

$$Q = \Delta H = 2(20.63) + 1(91.92) - 1(121.0) + (-40.77) = -28.59 \text{ kJ/g mol butadiene}$$

Alternately you can use tables of ΔH values or the CD that accompanies the book to get the ΔH_{Prod} and ΔH_{react} . The answer for the enthalpy change is -25.3 kJ.

Heat Transfer:

$$\Delta H_{1000} = [(-165.5)(1) - (-147.6)(1)] + 133.18 - 121.0 = -5.72 \text{ kJ/g mol}$$

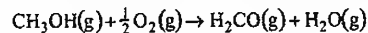
The actual heat load may be different because:

- (1) the reaction may not go to completion
- (2) side reactions are possible
- (3) the effect of pressure is not included
- (4) insulation may be bad

26.23

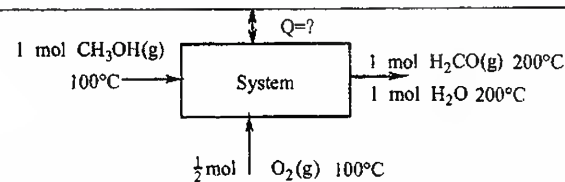
Steps 1, 2, 3, and 4:

This is a steady state problem involving an open system and reaction. All the temperatures for the stream flows are given and shown in the diagram. The reaction is



$$\Delta \hat{H}_f^\circ (\text{kJ/g mol}): \quad -201.25 \quad 0 \quad -115.89 \quad -241.826$$

Solutions Chapter 26



The results of the material balance are shown in the figure. The reference conditions are 25°C and 1 atm.

Step 5 Basis: 1 g mol $\text{CH}_3\text{OH}(\text{g})$

Steps 6, 7, 8, and 9

The energy balance reduces to

$$Q = \Delta H = \sum_{\text{products}} n_i \Delta \hat{H}_i - \sum_{\text{reactants}} n_i \Delta \hat{H}_i$$

We will use the heat capacity equations to calculate the sensible heats instead of the enthalpy tables. The balances will have the energy units of kJ.

$$\begin{aligned} \Delta H_{\text{Products}} &= 1 \left[-115.89 + (10^{-3}) \int_{25}^{200} (34.28 + 4.268 \times 10^{-3}T - 8.694 \times 10^{-9}T^3) dT \right] \\ &+ 1 \left[-241.826 + (10^{-3}) \int_{25}^{200} (33.46 + 0.688 \times 10^{-3}T + 0.7604 \times 10^{-5}T^2 - 3.593 \times 10^{-9}T^3) dT \right] \\ &= -115.89 + (10^{-3}) [5999 + 840.26 - 3.477] \\ &- 241.826 + (10^{-3}) [5855.5 + 135.45 + 20.238 - 1.43] \\ &= -115.89 + 6.84 - 241.826 + 6.010 \\ &= -344.87 \text{ kJ} \end{aligned}$$

(continued)

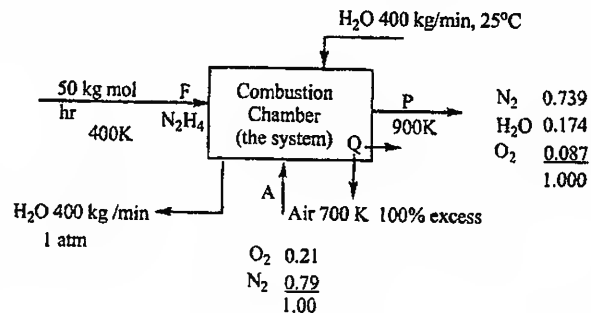
$$\begin{aligned}\Delta H_{\text{Reaction}} &= 1 \left[-201.25 + (10^{-3}) \int_{25}^{100} (42.93 + 8.301 \times 10^{-2} T - 1.87 \times 10^{-5} T^2 - 8.03 \times 10^{-9} T^3) dT \right] \\ &\quad + \frac{1}{2} \left[0 + (10^{-3}) \int_{25}^{100} (29.10 + 1.158 \times 10^{-2} T - 0.6076 \times 10^{-5} T^2 + 1.311 \times 10^{-9} T^3) dT \right] \\ &= 1 \left[-201.25 + (10^{-3}) (3219.75 + 389.109 - 6.136 - 0.19996) \right] \\ &\quad + \frac{1}{2} \left[0 + (10^{-3}) (2182.5 + 54.281 - 1.994 + 0.03265) \right] \\ &= -201.25 + 3.602 + 0 + 1.117 \\ &= -196.53 \text{ kJ}\end{aligned}$$

$$Q = -344.87 - (-196.53) = \boxed{-148.34 \text{ kJ/g mol CH}_3\text{OH}} \text{ (heat removed)}$$

26.24

Steps 1, 2, 3, and 4

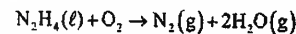
This is a steady state problem involving an open system and reaction. All the known data has been placed in the figure. The surroundings are an open system comprised of the water. N_2H_4 is liquid.



Step 5 Basis: 1 hour

Step 4

The reaction is



$$\Delta \hat{H}_f^\circ (\text{kJ/g mol}): \quad 44.77 \quad 0 \quad 0 \quad -241.826$$

The essential elements of the calculation of the air flow are:

$$\text{O}_2 \text{ required: } \frac{50 \text{ kg mol N}_2\text{H}_4}{1 \text{ kg mol N}_2\text{H}_4} \left| \frac{1 \text{ kg mol O}_2}{1 \text{ kg mol N}_2\text{H}_4} \right| = 50 \text{ kg mol O}_2$$

$$\text{O}_2 \text{ supplied: } \frac{50 \text{ kg mol O}_2 \text{ reqd}}{1 \text{ kg mol O}_2 \text{ reqd}} \left| \frac{2 \text{ kg mol O}_2 \text{ supplied}}{1 \text{ kg mol O}_2 \text{ reqd}} \right| = 100 \text{ kg mol O}_2$$

$$\text{N}_2 \text{ Supplied: } \frac{100 \text{ kg mol O}_2}{0.21 \text{ kg mol O}_2} \left| \frac{0.79 \text{ kg mol N}_2}{0.21 \text{ kg mol O}_2} \right| = 376.2 \text{ kg mol N}_2$$

$$\text{Air Supplied} = 476.2 \text{ kg mol}$$

Steps 5, 6, 7, 8 and 9

The material balances (in kg mol) for the process give are:

Balance	In	=	Out
O	200	=	$n_{\text{H}_2\text{O}} + 2n_{\text{O}_2}$
N	$50(2) + 2(376.3)$	=	$n_{\text{N}_2}(2)$
H	$50(4)$	=	$n_{\text{H}_2\text{O}}(2)$

The results are:

Out (kg mol)

(continued)

Solutions Chapter 26

$$n_{\text{H}_2\text{O}} = 100$$

$$n_{\text{N}_2} = 426.2$$

$$n_{\text{O}_2} = 50$$

$$\text{Total} = 576.2$$

The energy balance can be reduced to $Q = \Delta H$ for both the water and the combustion chamber. The reference state is 25°C and one atm. The first system is the combustion chamber.

System: Combustion Chamber

$$Q = \Delta H_{\text{products}} - \Delta H_{\text{reactants}} = \sum_{\text{products}} n_i \Delta \hat{H}_i - \sum_{\text{reactants}} n_i \Delta \hat{H}_i$$

We can use the heat capacity equations or the enthalpy tables to get $\Delta \hat{H}_i$.

Products	kg mol	T	$\Delta \hat{H}_f^\circ$ (kJ/kg mol)	$\Delta \hat{H}_{298K}^{\text{comb}}$ (kJ/kg mol)	ΔH (kJ)
H ₂ O (g)	100	900K	-241,826	(22,760-837)	-2.199×10^7
N ₂ (g)	426.2	900K	0	(18,961-728)	0.777×10^7
O ₂ (g)	50	900K	0	(19,970-732)	0.096×10^7
Total					-1.326×10^7

Reactants	kg mol	T	$\Delta \hat{H}_f^\circ$ (kJ/kg mol)	$\Delta \hat{H}_{298K}$ (kJ/kg mol)	ΔH (kJ)
N ₂ H ₄ (l)	50	400K	+44,770	(39,400-298)	2.947×10^6
O ₂ (g)	100	700K	0	(13,225-732)	1.249×10^6
N ₂ (g)	376.2	700K	0	(12,652-728)	4.4885×10^6
Total					8.685×10^6 kJ

$$Q = [-13.26 \times 10^6 - 8.685 \times 10^6] = -21.95 \times 10^6 \text{ kJ}$$

System – Water

Solutions Chapter 26

For the water $Q = \Delta H_{\text{out}} - \Delta H_{\text{in}}$. Find ΔH_{out} .

$$Q = +21.95 \times 10^6 \text{ kJ assuming no heat loss to the surroundings.}$$

$\Delta H_{\text{in}} = 0$ as material enters at 25°C.

$$\Delta \dot{H}_{\text{out}} = 21.95 \times 10^6 \text{ kJ/60} = 3.658 \times 10^5 \text{ kJ/min}$$

$$\Delta \dot{H}_{\text{out}} = \frac{3.658 \times 10^5 \text{ kJ}}{\text{min}} \left| \frac{1 \text{ min}}{400 \text{ kg}} \right| = 914 \text{ kJ/kg}$$

which corresponds to a mixture of liquid and vapor. At one atm and $\Delta \hat{H} = 914 \text{ kJ/kg}$ (relative to 25°C), the water can be a two phase system. The water vapor from the steam tables at 1 atm is $\Delta \hat{H}$ of saturated water vapor = 2675.6 - 107 = 2569 kJ/kg, and $\Delta \hat{H}$ for liquid water is 419.5 - 107 = 313 kJ/kg. Thus, the fraction vapor is

$$914 = 313(1-x) + 2569.6x$$

$$x = 0.266 \text{ a significant fraction of vapor}$$

Consequently, the exit line has to be quite large to accommodate the vapor and liquid flow rate which is: volume per kg = 0.266 (1.673) + 0.734 (0.001043) = 0.445 m³/kg. Multiply by 400 kg/min = 178 m³/min

26.25

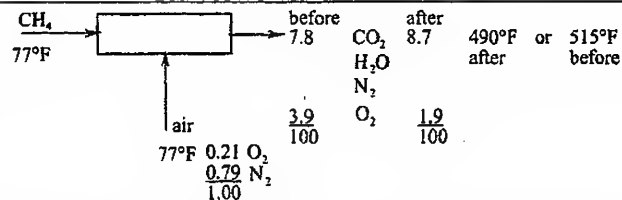
Material balance

Assume inputs are at 77°F, the reference temperature

Basis: 100g mol fg.

(continued)

Solutions Chapter 26

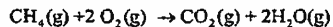


Both before and after the energy balance for an open steady state process reduces to $Q = \Delta H$. Assume that Q before = Q after.

Let P_1 = the g mol of flue gas before the change in xs air.

P_2 = the g mol of flue gas after the change in xs air.

The reaction is



ΔH_f° (kJ/g mol): -7484 0 -393.51 -241.826

The respective material balances are:

Case I – Before Basis: 100 g mol P

	IN		OUT
C:	n_{CH_4}	=	$n_{\text{CO}_2} = 7.8$
H:	$4n_{\text{CH}_4}$	=	$2n_{\text{H}_2\text{O}} \quad n_{\text{H}_2\text{O}} = 15.6$
2O:	$0.21A$	=	$7.8 + 3.9 + 0.5(15.6) = 19.5$

$$A = 19.5/0.21 = 92.86$$

$$n_{\text{N}_2} \text{ in} = n_{\text{N}_2} \text{ out} = 73.36$$

Solutions Chapter 26

$$n_{\text{O}_2} \text{ in} = 19.5$$

Summary

IN		OUT
7.8	CH ₄	-
19.5	O ₂	3.9
73.36	N ₂	73.36
-	CO ₂	7.8
-	H ₂ O	15.6
100.66		100.66

Case I – After Basis: 100 mol of P after

Summary

IN		OUT
8.7	CH ₄	-
19.3	O ₂	1.9
72.6	N ₂	72.6
-	CO ₂	8.7
-	H ₂ O	17.4
100.6		100.6

These values are good enough to get percents of each component.

Energy Balances

Case I – Before Assume reactants enter at 25°C (298 K), the reference T.

(continued)

Solutions Chapter 26

Comp.	g mol	T(K)	$\Delta \hat{H}_f^\circ$ (kJ/g mol)	$\Delta \hat{H}_{298}^\circ$ (kJ/g mol)	ΔH (kJ)
<u>IN</u>					
CH ₄	7.8	298	-74.84	0	-583.752
O ₂	9.5	298	0	0	0
N ₂	<u>73.36</u>	298	0	0	<u>0</u>
	100.66	298			-583.752
<u>OUT</u>					
CO ₂	7.8	541.5	-393.51	10.255	-2989.389
H ₂ O	15.6	541.5	-241.826	8.494	-3639.979
O ₂	3.9	541.5	0	7.462	29.102
N ₂	<u>73.36</u>	541.5	0	7.172	<u>526.133</u>
	100.66				-6074.128

Case II - After. Assume reactants enter at 25°C (298K). Let P = g mol fg. final

<u>IN</u>					
CH ₄	0.087P	298	-74.84	0	-6.511P
O ₂	0.193P	298	0	0	0
N ₂	<u>0.726P</u>	298	0	0	<u>0</u>
	1.006P				-6.511P

<u>OUT</u>					
CO ₂	0.087P	527.6	-393.51	9.640	-33.397P
H ₂ O	0.174P	527.6	-241.826	7.989	-40.688P
O ₂	0.019P	527.6	0	7.021	0.133P
N ₂	<u>0.726P</u>	527.6	0	6.757	<u>4.906P</u>
	1.006P				-69.045P

$$Q_{\text{before}} = \Delta H = -6074.128 - (-583.752) = -5490.4 \text{ kJ}$$

$$Q_{\text{after}} = Q_{\text{before}} = -5490.4 \text{ kJ} = \Delta H_{\text{out}} - \Delta H_{\text{in}} = [-69.045 - (-6.511)]P_{\text{after}}$$

$$= -62.534 P_{\text{after}}$$

Solutions Chapter 26

$$P_{\text{after}} = 87.80 \text{ g mol.}$$

$$87.80 (0.087) = \text{moles CH}_4 \text{ after} = 7.64 \text{ g mol vs. 7.8 before}$$

Energy used before $\times$ fraction saved is the savings

$$\frac{180,000 \text{ ft}^3 \text{ at SC}}{\text{hr}} \left| \frac{1 \text{ lb mol}}{359 \text{ ft}^3} \right| \left| \frac{454 \text{ g}}{1 \text{ lb}} \right| \left| \frac{5490.4 \text{ kJ}}{\text{g mol}} \right| \left| \frac{1 \text{ Btu}}{1.055 \text{ kJ}} \right|$$

$$\times \frac{\$1.55}{10^6 \text{ Btu}} \left| \frac{8000 \text{ hr}}{1 \text{ yr}} \right| \left| \frac{(7.80 - 7.64)}{7.80} \right| = \$1.94 \times 10^5 / \text{yr. Savings}$$

$$\frac{\$31,000}{1.94 \times 10^5} \left| \frac{\text{yr}}{\text{yr}} \right| = \boxed{0.16 \text{ yr}}$$

26.26

First, we estimate the heat recovery from the exhaust gas when cooled from 1100°F to 350°F, which is 100°F above the temperature of 15 psig saturated steam. Note we could use 220°F to get the maximum recovery.

From the tables with the initial and final exhaust gas temperatures, 1100°F and 350°F respectively, we determine the approximate heat recovery to be 198 Btu/lb exhaust gas.

To get the pounds of gas:

Knowing that the specific volume of the flue gas (the specific volume of flue gas at a given temperature is very close to the specific volume of air at that temperature.) at 1100°F is 39.5 cu ft/lb, we convert the exhaust flow rate from 4225 cfm to lb/h as follows:

Basis: 1 hr

(continued)

Solutions Chapter 26

$$\text{Exhaust flow rate} = \frac{4225 \text{ (cu ft/mi)} \times 60 \text{ (min/hr)}}{39.5 \text{ cu ft/lb}}$$

$$= 6420 \text{ lb/h}$$

$$\begin{aligned} \text{Then, rate of} &= 6420 \text{ lb/h} \times 198 \text{ Btu/lb} \\ \text{heat recovery} &= 1.27 \text{ MBtu/hr (or } 1.47 \times 10^6 \text{ Btu/hr if use } 220^\circ\text{F water)} \end{aligned}$$

2. Next, we calculate the amount of steam generated from the exhaust heat recovered. We determine that with 220°F feedwater the heat absorbed in generating 15 psig saturated steam is 977 Btu/lb steam.

$$\text{Steam generation} = \frac{1.27 \text{ MBtu/hr}}{977 \text{ Btu/lb}} = 1300 \text{ lb/hr (or } 1470 \text{ lb/hr if use } 220^\circ\text{F water)}$$

Thus, steam generation from the fired boiler will be reduced from 2000 lb/h to 700 lb/hr.

3. The resulting annual fuel savings with 80% boiler efficiency based on the lower heating value of the #2 fuel oil (18,300 Btu/lb oil) and assuming 4500 hours of operation per year are calculated below:

$$\begin{aligned} \text{Annual fuel savings} &= \frac{1.27 \text{ MBtu/hr} \times 4500 \text{ hr/yr}}{0.8} \\ &= \boxed{7140 \text{ MBtu/yr}} \end{aligned}$$

Knowing that the fuel oil density is about 7.02 lb/gal, we figure the annual fuel savings in gallons.

$$\begin{aligned} \text{Annual fuel savings} &= \frac{7140 \text{ MBtu/yr}}{18,300 \text{ Btu/lb} \times 7.02 \text{ lb/gal}} \\ &= \boxed{55,600 \text{ gal/yr}} \end{aligned}$$

4. If the #2 fuel oil costs \$0.50/gal,

Solutions Chapter 26

$$\text{Annual savings} = 55,600 \text{ gal/yr} \times \$0.50/\text{gal}$$

$$= \boxed{\$27,800 \text{ per year}}$$

The total cost of a waste heat recovery muffler and installation is about \$20 000 for a 500 hp engine. In this case, the installation can be paid off in about two to three years.

26.27

Basis: 10.0 min

The thermodynamic properties are from the Chemical Engineer's Handbook. The attached plot is used for quicker interpolation using $^\circ\text{F}$ instead of K for temperature. The data for n-G based on liquid Cp's and ΔH 's have been extrapolated from the handbook data.

The hot liquid will flash with no change in total enthalpy. Thus, the fraction vaporized has to be calculated.

To calculate fraction of liquid vaporized

$\dot{V}$ = Vapor rate

$\dot{F}$ = Spill (feed) rate

$$\frac{\dot{V}}{\dot{F}} = \frac{h_f - h_l}{H_v - h_l}$$

h_f = Enthalpy of spilled liq

h_l = Enthalpy of flashed liq

H_v = Enthalpy of flashed vap

$\dot{V}$ and $\dot{F}$ have mass or mole units

Specific gravity of solvents at 400°F :

CH_3OH : 0.529

$n - \text{C}_7$: 0.489

(continued)

Solutions Chapter 26

To calculate vapor

$$\Delta H_{\text{liquid in}} = \Delta H_{\text{liquid out}} + \Delta H_{\text{vapor out}}$$

$$m_{\text{Liquid in}} \Delta \hat{H}_{\text{liquid in}} = m_{\text{L out}} \Delta \hat{H}_{\text{L out}} + m_{\text{vapor out}} \Delta \hat{H}_v$$

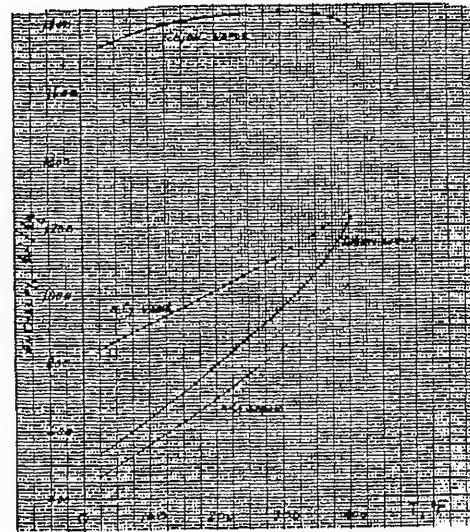
$$\text{plus } m_{\text{L in}} = m_{\text{L out}} + m_{\text{vapor}}$$

Spill Rates:

$$\text{CH}_3\text{OH} \quad 1000 \frac{\text{gal}}{\text{min}} (0.529)(8.35) \frac{\text{lb}}{\text{gal}} = 4417 \frac{\text{lb}}{\text{min}}$$

$$\text{n-C}_7 \quad 1000 \frac{\text{gal}}{\text{min}} (0.489)(8.35) \frac{\text{lb}}{\text{gal}} = 4083 \frac{\text{lb}}{\text{min}}$$

Solutions Chapter 26



		h_{vapor}	h_L	H_v	V_{vapor}
		kJ/kg			lb/min
CH ₃ OH	25°F	1210	530	1730	2503
	80°F	1210	605	1770	2793
	BP	1210	708	1805	2021
nC ₇	25°F	1030	465	840	4083 (all vapor)
	80°F	1030	542	890	4083 (all vapor)
	BP	209°F	1030	701	1022

(Note that all the n-heptane always flashes to vapor. Hydrocarbons generally have low heats of vaporization.)

(continued)

To get volume of vapor

The lower flammable limits of the solvents are (LFL is concentration air) This would be used to get idea of excess (or deficit) of air

For $\text{CH}_3\text{OH} \rightarrow 6.7\%$ $n\text{-C}_7 \rightarrow 1.05\%$

The volume of vapor is

v_v = specific volume of vapor

$$V_v = \dot{V} t v_s \quad t = \text{spill time}$$

and the volume of the maximum flammable vapor cloud is

$$\frac{V_v}{\text{LFL}} = \frac{\dot{V} t v_v}{\text{LFL}}$$

The specific volumes are

Using v_v at 80°F

$$v_v = \frac{RT}{p} = \frac{(10.73)(\text{ft}^3/\text{psia})(540)(^\circ\text{R})}{(\text{lb mol})(^\circ\text{R})(14.7)(\text{psia})(32)(\text{lb})} \quad (\text{lb mol})$$

$$= 12.32 \frac{\text{ft}^3}{\text{lb}} \quad \text{for } \text{CH}_3\text{OH}$$

$$v_v = \frac{(10.73)(540)}{(14.7)(98)} = 4.02 \frac{\text{ft}^3}{\text{lb}} \quad \text{for } n\text{-C}_7$$

The vapor cloud volumes are:

For CH_3OH at 80°F

$$\frac{(2793)(\text{lb})(10) \min (12.32) \text{ft}^3}{(\text{min}) (\text{lb})(0.067)} = \boxed{5.14(10^6) \text{ft}^3}$$

For $n\text{-C}_7$

$$\frac{(4083)(10)(4.02)}{(0.0105)} = \boxed{15.6(10^6) \text{ft}^3}$$

Therefore, choose methanol

Use criteria of ΔH . Assume stoichiometric amount of air for 25°C input (input T makes little difference). Ignore sensible heats.

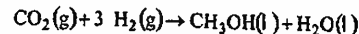
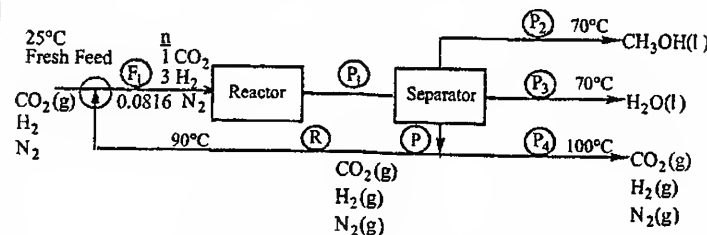
	$n\text{C}_7$	CH_3OH	
heats of combustion are	19,157	8,592	Btu/lb
mass burned	4,083	2,503	lb
energy released	78(10 ⁶)	21(10 ⁶)	Btu

So, still choose CH_3OH .

26.28

Step 5

Basis: 1 kg mol CO_2 in Gross Feed F_1



$25^\circ\text{C} = 298\text{K}$

$70^\circ\text{C} = 343\text{K}$

$100^\circ\text{C} = 373\text{K}$

Step 4

(continued)

Solutions Chapter 26

Material Balance to get N_2 in gross feed to the reactor. Assume concentration is 2.0% (the maximum allowed).

$$0.02 = \frac{n_{N_2}}{1 + 3 + n_{N_2}} \quad n_{N_2}^F = 0.0816 \text{ mol/mol } F_1$$

System: Reactor plus separator

Steps 6 and 7

Number of equations (5): 4 element balances + fraction conversion

	(F ₁)	=	(P ₂)	+	(P ₃)	+	(P)
C:	1	=	P ₂ (1)	+	0	+	$n_{CO_2}^P$
H:	3(2)	=	P ₂ (4)	+	2P ₃	+	$n_{H_2}^P$ (2)
O:	1(2)	=	P ₂ (1)	+	P ₃ (1)	+	$n_{CO_2}^P$ (2)
N ₂	0.0816	=	P ₂ (0)	+	P ₃ (0)	+	$n_{N_2}^P$

Species balance:

	in	-	out	+ gen	-	consumed
CO ₂ balance:	1	-	$n_{CO_2}^P$	+ 0	-	0.57(1)

Unknowns (5): $P_2, P_3, n_{CO_2}^P, n_{H_2}^P, n_{N_2}^P$

Note: $P = \sum n_i^P$ is redundant.

Solution of equations (all in kg mol)

$$P_2 = 0.57 \quad x_{CO_2}^P = \frac{0.43}{1.8016} = 0.239$$

$$P_3 = 0.57$$

Solutions Chapter 26

$$n_{CO_2}^P = 0.43 \quad x_{H_2}^P = \frac{1.29}{1.8016} = 0.716$$

$$n_{H_2}^P = 1.29$$

$$n_{N_2}^P = 0.0816 \quad x_{N_2}^P = \frac{0.0866}{1.8016} = 0.045$$

$$P = \sum n_i^P = 1.8016$$

System: mixing point before reactor (no reaction occurs)

Unknowns (2): F and R; Equations (2): Total and N₂

$$\text{Total: } F + R = 4.0816 = F_1$$

$$\text{Nitrogen: } N_2: 0.005F + x_{N_2}^R R = 0.0816$$

After F and R are calculated as below $F = F_1 - R$ (no reaction)

$$F = 2.562 \text{ kg mol} \quad R = 1.520 \text{ kg mol}$$

$$n_{CO_2}^F = 1 - 1.520(0.239) = 0.677 \text{ kg mol}$$

$$n_{H_2}^F = 3 - 1.520(0.716) = 1.912 \text{ kg mol}$$

$$n_{N_2}^F = 0.0816 - 1.520(0.045) = 0.0128$$

$$\text{Check: } 0.005(2.526) = 0.0128$$

All mol values are in kg mol

System: sep. point after separator

(continued)

Solutions Chapter 26

 $P_4 = P - R$ & for each component

$$P_4 = 1.802 - 1.520 = 0.282$$

$$n_{\text{CO}_2}^P = \left(\frac{0.43}{1.802} \right) 0.282 = 0.067$$

$$n_{\text{H}_2}^P = \left(\frac{1.29}{1.802} \right) 0.282 = 0.336$$

$$n_{\text{N}_2}^P = \left(\frac{0.0816}{1.802} \right) 0.282 = 0.0128$$

Energy Balance (ref. 25°C) an overall system

$$\Delta E = Q + W - \Delta H$$

$$\Delta E = W = 0$$

$$Q = \Delta H = \Delta H_{\text{prod}} - \Delta H_{\text{react}}$$

OUT

			kg J/kg mol		
	Comp.	kg mol	$\Delta \hat{H}_r^\circ$ (kJ/kg mol)	$\Delta \hat{H}_{\text{sens}}$ (kJ/kg mol)	ΔH (kJ)
70°C	CH ₃ OH (ℓ)	0.57	-238,640	(70-25)(4.184)(.680)(32)	-133,690
70°C	H ₂ O (ℓ)	0.57	-285,840	(70-25)(4.184)(18)	-160,997
100°C	CO ₂ (g) in P ₄	0.067	-393,510	(3045-912)	-26,222
100°C	H ₂ (g) in P ₄	0.336	0	(2874-718)	724
100°C	N ₂ (g) in P ₄	0.0128	0	(2910-728)	28
					<u>-320,157</u>

IN

25°C	CO ₂ (g)	0.677	-393,510	0	-266,406
25°C	H ₂ (g)	1.912	0	0	0
100°C	N ₂ (g)	0.0128	0	0	0
					<u>-266,406</u>

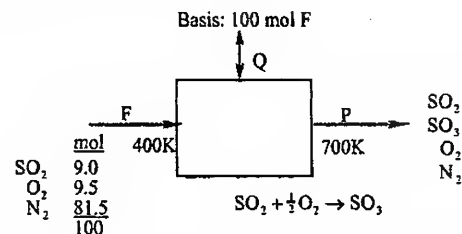
$$Q = -320,157 - (-266,406) = -53,751 \text{ kJ (heat removed)}$$

The overall result is

$$\frac{53,751 \text{ kJ}}{2.562 \text{ kg mol F}} = \boxed{20,980 \text{ kJ/g mol fresh feed}}$$

Solutions Chapter 26

26.29

Steady state, no W, no P, no K so $Q = \Delta H$ 

Material balance

$$\begin{aligned} S \begin{cases} 9.0(0.75) \\ 9.0(0.25) \end{cases} &= n_{\text{SO}_2}^P \\ &= n_{\text{SO}_2}^P \\ N_2: 81.5 &= n_{\text{N}_2}^P \\ O_2: 9.0 + 9.5 &= n_{\text{SO}_2}^P(1.5) + n_{\text{SO}_2}^P(1) + n_{\text{O}_2}^P(1) \\ n_{\text{O}_2}^P &= 18.5 - 1.5(6.75) - 2.25 = 6.125 \end{aligned}$$

$$\text{Ref. } T = 25^\circ\text{C} = 298\text{K}$$

$$\dot{Q} + \dot{W} = \Delta \dot{H} \quad \text{steady state, flow, no W, P, K; } Q = 0$$

$$\Delta H = 0$$

OUT

Component	mol	T(K)	$\Delta \hat{H}_r^\circ$ (J/gmol)	"Sensible heat" $\Delta \hat{H}$ (J/gmol)	ΔH (J)
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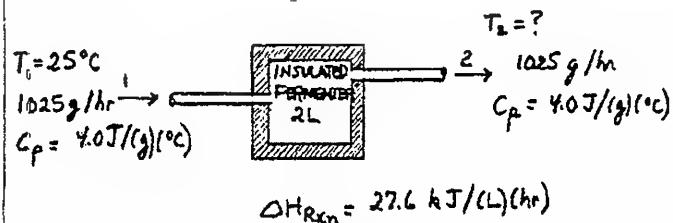
(continued)

Solutions Chapter 26

SO ₂ (g)	2.25	700K	-296,900	(19,501-984)	-626,361.8
SO ₃ (g)	6.75	700K	-395,180	(27,154-1255)	-2,492,646.8
N ₂ (g)	81.5	700K	0	(12,652-728)	971,806.0
O ₂ (g)	6.125	700K	0	(13,225-732)	76,519.6
					-2,070.683
IN					
SO ₂ (g)	9.0	400K	-296,900	(5,234-984)	-2,633,850
O ₂	9.5	400K	0	(3,752-732)	28,690
N ₂ (g)	81.5	400K	0	(3,695-728)	241,810.5
					-2,363,349.5

$$Q = [\sum \Delta H_{\text{Prod}} - \sum \Delta H_{\text{React}}] = \boxed{32.52 \frac{\text{kJ}}{\text{g mol}}}$$

26.30



Open steady state system: the inside of the cell.

$$\Delta H + Q + W \quad Q = 0 \quad W = 0$$

$$\Delta H = 0$$

$$\Delta H_{\text{str}} + \Delta H_{\text{rxn}} = 0$$

$$m_2 C_{p2} (T_2 - T_{\text{ref}}) - m_1 C_{p1} (T_1 - T_{\text{ref}}) + \Delta H_{\text{rxn}} = 0$$

Solutions Chapter 26

Let $T_{\text{ref}} = 25^\circ\text{C}$

$$\frac{1 \text{ hr}}{1} \left| \frac{1025 \text{ g}}{\text{hr}} \right| \left| \frac{4.0 \text{ J}}{(\text{g})(^\circ\text{C})} \right| (T_2 - 25^\circ\text{C}) - \frac{1 \text{ hr}}{1} \left| \frac{1025 \text{ g}}{\text{hr}} \right| \left| \frac{4.0 \text{ J}}{(\text{g})(^\circ\text{C})} \right| (25 - 25)^\circ\text{C}$$

$$+ \frac{1 \text{ hr}}{1} \left| \frac{27.6 \text{ kJ}}{(\text{L})(\text{hr})} \right| \left| \frac{2 \text{ L}}{1000 \text{ J}} \right| \frac{1}{\text{kJ}} = 0$$

$$T_2 = \frac{(55,200 + 102,500) \text{ J}}{4,100 \text{ J/}^\circ\text{C}} = \boxed{38^\circ\text{C, yes}}$$

27.1

Basis: 1 lb butane

a. $\dot{W} = - \int_{V_1}^{V_2} p dV$ Assume a batch process. Vaporization is at constant p .

70 kPa $\approx$ 10 psia. The value is off of the butane chart in the text. Instead use the CD to get the boiling point at 10.16 psia of 14.3°F. Use the ideal gas law to get

$$\hat{V}_{\text{vapor}} = 8.63 \text{ ft}^3/\text{lb} \text{ or } 0.539 \text{ m}^3/\text{kg}.$$

$$\hat{V}_{\text{liquid}} = 0.026 \text{ ft}^3/\text{lb} \text{ from Perry or } 0.00162 \text{ m}^3/\text{kg}.$$

Basis: 1 kg butane

$$\dot{W} = -p\Delta\hat{V} = -\frac{70 \times 10^3 \text{ N}}{\text{m}^2} \left| \frac{(0.539 - 0.00162) \text{ m}^3}{\text{kg}} \right| \frac{1 \text{ J}}{1 (\text{N})(\text{m})} = \boxed{-3.76 \times 10^4 \text{ J/kg}}$$

b. The energy balance cannot be used to calculate W because Q is not known. If Q is known,

$$\Delta\hat{E} = \hat{Q} + \hat{W} \text{ so } -\hat{W} = \hat{Q} - \Delta\hat{E} = \hat{Q} - (\Delta\hat{H} - p\Delta\hat{V})$$

27.2

Basis: 1 lb mole H_2O

Process: reversible batch, open system, no reaction. System: vessel of water.

$$E_2 - E_1 = Q + W - \Delta H - \Delta KE - \Delta PE \quad \Delta KE = 0 \quad \Delta PE = 0$$

This equation will not lead to a single unknown, W , from the data given. Because the process is reversible (since the temperature and pressure are constant)

$$\hat{W}_{\text{rev}} = - \int p dV = -p\Delta\hat{V}. \text{ Work is done against the atmosphere at constant}$$

pressure

$$\Delta\hat{V} \text{ from Steam Tables} = (26.81 - 0.0167) \text{ ft}^3/\text{lb}$$

$$W = -\frac{14.7 \text{ lb}}{\text{in}^2} \left| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right| \frac{(26.81 - 0.0167) \text{ ft}^3}{\text{lb}} \left| \frac{1 \text{ Btu}}{778 (\text{ft})(\text{lb}_f)} \right| \frac{18 \text{ lb}}{1 \text{ lb mol}}$$

$$= \boxed{-1313 \text{ Btu/lb mol}}$$

27.3

Basis: 1 kg steam Paths are not shown but the data are:

State 1	State 2	State 3	State 4	State 5	Units
540	540	199	143	425	T(°C)
2700	700	400	400	2700	p(kPa)
0.1361	0.5339	0.5339	0.4625	0.1161	$\hat{V}(\text{m}^3/\text{kg})$
3542	3558	2862	2733	3285	$\Delta\hat{H}(\text{kJ/kg})$

Closed, unsteady state system

Energy balance: $Q + W = \Delta U$ Reversible work: $W_{\text{rev}} = - \int_{V_1}^{V_2} p dV$ State 1 to State 2 at constant $T = 540^\circ\text{C}$

$$\Delta\hat{H} = 3558 - 3542 = 16 \text{ kJ/kg}$$

(continued)

$$\Delta \hat{U} = \Delta \hat{H} - \Delta(p\hat{V}) = 16 - [(700)(0.5339) - (2700)(0.1361)] = \boxed{9.7 \text{ kJ/kg}}$$

or calculate use ΔU directly from the CD.

If reversibility is assumed, W_{rev} can be calculated by selecting $(p, \hat{V})$ pairs along an isotherm and integrating the area under a plot of p vs $\hat{V}$. Q then can be calculated from $Q = \Delta U - W$.

State 2 to State 3 at constant V

$$\Delta \hat{H} = 2862 - 3558 = -696 \text{ kJ/kg}$$

$$\Delta \hat{U} = -696 - [(400)(0.5339) - 700(0.5339)] = -535.8 \text{ kJ/kg}$$

$$W_{\text{rev}} = 0 \text{ as } \Delta V = 0$$

$$Q = \Delta U = \boxed{-535.8 \text{ kJ/kg}}$$

State 3 to State 4 at constant p

$$\Delta \hat{H} = 2733 - 2862 = -129 \text{ kJ/kg}$$

$$\Delta \hat{U} = -129 - [(400)(0.4625) - (400)(0.5339)] = -100 \text{ kJ/kg}$$

$$W_{\text{rev}} = -p\Delta V = 40(0.4625 - 0.5339) = 28.6 \text{ kJ/kg}$$

$$Q = \Delta U - W = -100 - (+28.6) = \boxed{-129 \text{ kJ/kg}}$$

State 4 to State 5 with $Q \approx 0$

$$\Delta \hat{H} = 3285 - 2733 = 552 \text{ kJ/kg}$$

$$\Delta \hat{U} = 552 - [(2700)(0.1161) - (400)(0.4625)] = 423.5 \text{ kJ/kg}$$

$$Q = 0$$

$$-W = Q - \Delta U = -423.5 \text{ kJ/kg or } W = \boxed{423.5 \text{ kJ/kg}}$$

State 5 to State 1

$$\Delta \hat{H} = 3542 - 3285 = 257 \text{ kJ/kg}$$

$$\Delta \hat{U} = 257 - [(2700)(0.1361) - (2700)(0.1161)] = 203 \text{ kJ/kg}$$

$$Q = ?$$

$$W_{\text{rev}} = ? \text{ (cannot be calculated because path is unknown)}$$

Check

$$\text{Is } \Delta H \approx 0, \text{ yes; Is } \Delta H \approx 0; \Delta U = 0.43 \text{ which is close enough?}$$

27.4

Basis: 1 lb mol H_2O

Initial State

Water at 212°F
and 1 atm (enthalpy = ΔH_1)

Final State

Saturated steam at 212°F
and 1 atm (enthalpy = ΔH_2)

- a. Steady state open (flow) process: flow in a pipeline, negligible kinetic and potential energy changes. No work is done by the system or on the system so that $W = 0$, and,

$$\boxed{W = 0}$$

- b. Closed (non-flow) process: The basic equation is:

$$\Delta U_2 - \Delta U_1 = \Delta U = Q + W$$

(continued)

Because the work done is only a volume expansion and is reversible

$$\dot{W} = -\int_{\hat{V}_1}^{\hat{V}_2} p d\hat{V} = -p\Delta\hat{V} = -(p\hat{V}_2 - p\hat{V}_1)$$

Obtain $\hat{V}_1$, $\hat{V}_2$ from steam tables

$$W = -p\left(\frac{\text{lb}_f}{\text{ft}^2}\right)[V_2 - V_1]\text{ft}^3 = -(14.7)(144)(26.799 - 0.016719)$$

$$= -56.677 \frac{(\text{ft})(\text{lb}_f)}{\text{lb steam}} = -72.85 \frac{\text{Btu}}{\text{lb}} = -1,312 \frac{\text{Btu}}{\text{lb mol}}$$

Work is done against the atmosphere.

27.5

Basis: Adiabatic expansion with no work, a flow process.

$$W = 0 \quad \text{irreversible expansion}$$

$$Q = 0$$

a. $Q + W = \Delta H = 0$

An example is an ideal gas expanding through a restriction; H is a function of T only, and if $\Delta H = 0$, $\Delta T = 0$.

b. Expansion of a real gas is not isothermal

$$\int dH = \int \left(\frac{dH}{dT}\right) dT + \int \left(\frac{dH}{dp}\right) dp = \int C_p dT + \int \left[V - T\left(\frac{dV}{dT}\right)_p\right] dp = 0$$

For a nonideal gas, $C_p dT$ can be offset by the second term.

27.6

System: 1 lb mol of N_2 in the cylinder.

Compute the change in volume of the N_2 . The initial volume is

$$V_1 = \frac{znRT_1}{p_1}$$

$z = 1.00$ (calculations not shown)

$$V_1 = \frac{1 \text{ lb mol}}{14.7 \text{ psia}} \left| \frac{10.73(\text{psia})(\text{ft}^3)}{(\text{lb mol})(^\circ\text{R})} \right| \frac{760^\circ\text{R}}{14.7 \text{ psia}} = 554.7 \text{ ft}^3$$

$$\Delta V = 0.5(554.7) = 227.4 \text{ ft}^3/\text{lb mol}$$

a. While the N_2 compression is irreversible, the work done by the steam on the piston may be approximately reversible because p is constant and the reservoir is large so that the steam conditions are essentially constant with expansion on top of the piston. If so:

$$W = -\int p dV = -p\Delta V = -\frac{70 \text{ lb}_f}{\text{in}^2} \left| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right| \frac{227.4 \text{ ft}^3}{\text{lb mol}} \left| \frac{1 \text{ Btu}}{778(\text{ft})(\text{lb}_f)} \right|$$

$$= -2946 \text{ Btu/lb mol}$$

b. The work done on the piston by the steam may not all be transferred to the N_2 because of the irreversibility of the compression of the N_2 by the piston. If it were reversible, then the work done on the N_2 would be computed as below.

c. The energy balance for the piston is, if a reversible process occurred would be

$$\Delta U + \Delta PE = Q + W$$

$$Q = 0 \quad W = +2946 \text{ Btu}$$

(continued)

Solutions Chapter 27

 ΔPE (of the piston) = ?

Calculate the change in height of the piston.

$$A = \frac{\pi \left(\frac{10}{12}\right)^2}{4} = 0.545 \text{ ft}^2$$

$$\Delta h \text{ of piston} = \frac{0.611 \text{ ft}^3}{0.545 \text{ ft}^2} = 1.12 \text{ ft}$$

$$\Delta PE = mg\Delta h = \frac{10 \text{ lb}}{1} \left| \frac{32.2 \text{ ft}}{\text{s}^2} \right| \left| \frac{(\text{lb}_f)(\text{s}^2)}{32.2(\text{lb})(\text{ft})} \right| \left| \frac{-1.12 \text{ ft}}{1} \right| \left| \frac{1 \text{ Btu}}{778(\text{ft})(\text{lb}_f)} \right|$$

$$= -0.014 \text{ Btu} \quad (\text{can be neglected})$$

$$\Delta U = 0 + 2946 + 0.014 = 2946 \text{ Btu}$$

If all of this energy were transferred to the N_2 on compression (unlikely), ΔU of the N_2 ; otherwise, ΔU of the piston and cylinder would go up and the ΔU would be 2946 Btu/lb mol N_2 of the N_2 would not go up as much as 2946 Btu/lb mol N_2 .

27.7

$$\begin{aligned} \text{Efficiency} &= \frac{\text{hp output}}{\text{hp input}} \times 100\% \\ &= \frac{24.6 \text{ hp}}{30 \text{ hp}} \times 100\% = \boxed{82\%} \end{aligned}$$

Solutions Chapter 27

27.8

$$\text{Annual cost} = \frac{300,000 \text{ kW}}{1} \left| \frac{6000 \text{ hr}}{1} \right| \left| \frac{3.4128 \times 10^3 \text{ Btu}}{1 \text{ kW hr}} \right| \left| \frac{\$1.10}{10^6 \text{ Btu}} \right| \left| \frac{1}{0.40} \right|$$

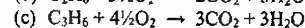
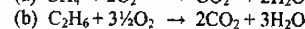
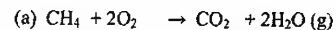
$$= 1.69 \times 10^7 / \text{yr.}$$

27.9

Basis: 100 g mol Fg

Material balances

Chemical reaction equations



$$\text{Excess O}_2: 202.535 (.10) = 20.25 \text{ g mol}$$

$$\text{Total O}_2: 202.535 + 20.25 = 222.79 \text{ g mol}$$

$$\text{N}_2 \text{ entering: } 222.79(79/21) = 838.11 \text{ g mol}$$

	g mol	req'd O ₂	CO ₂ produced	H ₂ O produced	$\Delta \hat{H}_f^\circ$ (kJ/g mol)
CH ₄	96.4	192.8	96.4	192.8	-74.84
C ₂ H ₆	2.01	7.035	4.02	6.03	-84.667
C ₃ H ₆	0.6	2.7	1.8	1.8	20.41
N ₂	0.99				0
Total		202.535	102.22	200.63	

(continued)

Exit flue gas ($T = 450^\circ\text{C}$)

	<u>g mol</u>	<u>$\Delta\hat{H}_{\text{sensible}}$ (kJ/g mol)*</u>	<u>ΔH (kJ)</u>
CO ₂	102.22	18.599	1,901.19
H ₂ O	200.63	15.304	3,070.44
N ₂	839.1	12.690	10,648.18
O ₂	20.25	13.366	270.66
	Total		15,891

*From the CD

To get the LHV, Use the values from Appendix F to get the heat of reaction at SC with H₂O(g) as the product. O₂ and N₂ have 0 $\Delta\hat{H}_f^\circ$.

Reaction (a):

$$\Delta H_{\text{rxn}}^\circ = 96.4(-393.51) + 192.8(-241.826) - 96.4(-74.84) = \frac{\text{kJ/100 g mol gas}}{-77,348}$$

Reaction (b):

$$\Delta H_{\text{rxn}}^\circ = 4.02(-393.51) + 6.03(-241.826) - 2.01(-84.667) = -2,870$$

Reaction (c):

$$\Delta H_{\text{rxn}}^\circ = 1.8(-393.51) + 1.8(-241.826) - 0.6(20.41) = -1,131$$

Total -81,349

LHV = 81,349 kJ/100 g mol

$$\text{Efficiency} = 100 - \left[\frac{0.02(81,349)}{81,349} - \frac{15,891}{81,349} \right] 100 = \boxed{82\%}$$

27.10

Basis: 1 second

Convert all of the data to J as needed. The process is steady state.

Electric output 500,000 kW $\rightarrow 5 \times 10^5$ kJEnergy with fuel input

$$E_{\text{fuel}} = (64.6 \text{ kg}) (28,400 \text{ kJ/kg}) = 1.349 \times 10^6 \text{ kJ}$$

Heat added to the steam (system is boiler). Data are from the CD.

$$Q = \Delta H = m_{\text{steam}} (\hat{H}_{\text{out}} - \hat{H}_{\text{in}}) = 640(3,175.9 - 647.0)$$

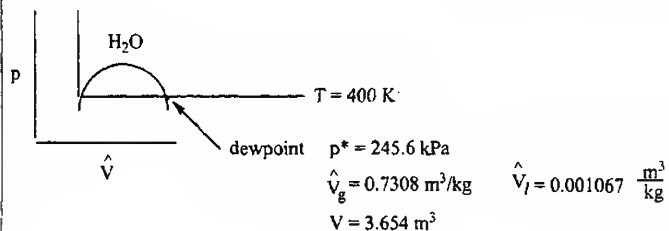
$$= 1.619 \times 10^6 \text{ kJ}$$

$$\text{Boiler efficiency} = \frac{1.619 \times 10^6 \text{ kJ}}{1.834 \times 10^6 \text{ kJ}} (100) = \boxed{88.3\%}$$

$$\text{Gross plant efficiency} = \frac{5 \times 10^5 \text{ kJ}}{1.834 \times 10^6 \text{ kJ}} (100) = \boxed{27.2\%}$$

$$\text{Steam cycle efficiency} = \frac{5 \times 10^5 \text{ kJ}}{1.619 \times 10^6 \text{ kJ}} (100) = \boxed{30.9\%}$$

27.11

Basis: 5 kg H_2O

The process is reversible (conversion of vapor to liquid at constant temperature and pressure).

a. Initially, all the H_2O is vapor (i.e., at the dew point) so the volume of liquid was 0.

b. $W = -\int_{V_1}^{V_2} p dV = -p \int_{V_1}^{V_2} dV = -p(V_2 - V_1) = 400 \text{ kJ}$

$$\frac{245.6 \text{ kPa} \left| (V_2 - 3.654) \text{ m}^3 \right|}{\frac{1 \text{ J}}{1 \text{ (kg)(m}^2\text{)}} \frac{1 \text{ (kg)(m)}}{\text{s}^2}} \frac{1 \text{ Pa}}{1 \text{ Pa}} = 400 \text{ kJ}$$

$$-(V_2 - 3.654) = 1.629$$

$$V_2 = 2.025 \text{ m}^3$$

$$\hat{V} = \frac{2.025 \text{ m}^3}{5 \text{ kg}} = (1-x)(0.001067) + x(0.7308) = 0.4050 \frac{\text{m}^3}{\text{kg}}$$

where x = mass fraction vapor $x = 0.554$

The volume of liquid was $(1-x)(5)(0.001067) = \boxed{0.0024 \text{ m}^3}$ after compression.

27.12



$$\Delta \widehat{PE} + \Delta \widehat{KE} + \int_{V_1}^{V_2} \hat{V} dp - \hat{W} + \hat{E}_v = 0 \quad \text{used to calculate } \hat{E}_v$$

Basis: 1 min (1000 L)

$$\frac{1000 \text{ L}}{1000 \text{ L}} \left| \frac{1 \text{ m}^3}{1000 \text{ L}} \right| = 1 \text{ m}^3$$

The density of water is 1000 kg/m^3

$$\int \hat{V} dp = \hat{V} \Delta p \quad \text{for a liquid}$$

$$m \hat{V} \Delta p = 10^3 \text{ kg} \frac{10^{-3} \text{ m}^3}{\text{kg}} \left| \frac{(290 - 140) 10^3 \text{ N}}{\text{m}^2} \right| \frac{1 \text{ J}}{1 \text{ (N)(m)}} = 150 \text{ kJ}$$

$$\Delta(\widehat{PE}) = 0 \quad W = 0 \quad \Delta \widehat{KE} = 0$$

$$\hat{E}_v = -\dot{m} \hat{V} \Delta p = -150 \text{ kJ/min}$$

(continued)

To calculate the temperature change, for a throttling process the energy balance reduces to $\Delta H = 0$.

$$\begin{array}{ccc} \text{in} & & \text{out} \\ \text{liquid} & & \Delta \hat{H} = 20.8 \text{ at } 140 \text{ kPa} \\ \Delta \hat{H} = 20.8 & & \end{array}$$

$$0 = \Delta \hat{H} = \int C_p dT + \int \left(\frac{\partial \hat{H}}{\partial p} \right)_T dp$$

But the second term for a liquid is approximately zero, hence $\Delta T \cong 0$

27.13

Process: flow, steady state System: feed water pump

$$\Delta(\hat{K}\dot{E} + \hat{P}\dot{E}) + \int \hat{V} dp - \dot{W}_{rev} + \hat{E}_v = 0$$

Application of the general equation for the conservation of energy is not too useful since it reduces to, $Q + W = \Delta H$. By assuming a reversible process and applying the given efficiency factor, one obtains the work per time done on the system.

$$W_{rev} = \int_{p_1}^{p_2} V dp$$

If V is constant, $W_{rev} = + V \Delta p$.

$$p_2 = 500 \text{ psia}$$

$$p_1 = 0.9 \text{ psia}$$

Basis: 100 gal/min

$$\frac{100 \text{ gal}}{\text{min}} \left| \frac{1 \text{ (ft)}^3}{7.48 \text{ gal}} \right| \frac{(500 - 0.9) \text{ (lb}_p\text{)}}{(\text{in})^2} \left| \frac{144 \text{ (in)}^2}{(\text{ft})^2} \right| \frac{1 \text{ min}}{60 \text{ sec}} \left| \frac{1 \text{ (hp)}}{550 \text{ (ft) (lb}_p\text{)}} \right| \frac{\text{sec}}{0.40} = 72.8 \text{ hp}$$

27.14

Mechanical energy balance:

$$\Delta(\hat{K}\dot{E} + \hat{P}\dot{E}) = \int_{p_1}^{p_2} \hat{V} dp - \dot{W} + \hat{E}_v = 0$$

The minimum work is the reversible work so $\hat{E}_v = 0$. Then

$$\int_{p_1}^{p_2} \hat{V} dp = \dot{W} \Delta p$$

because the fluid is incompressible, but $\Delta p = 0$. Thus the mechanical energy balance reduces to

$$W_{rev} = \Delta[(\hat{K}\dot{E} + \hat{P}\dot{E})m]$$

If $\dot{m}$ is the mass/time then, $\dot{W}$ = work/time = power

$$\dot{W} = (\hat{K}\dot{E}_4 + \hat{P}\dot{E}_4)\dot{m}_4 + (\hat{K}\dot{E}_2 + \hat{P}\dot{E}_2)\dot{m}_2 - (\hat{K}\dot{E}_1 + \hat{P}\dot{E}_1)\dot{m}_1$$

where the subscripts refer to the floors.

Basis: flows of water as shown in Figure in text (i.e., 1 min)

Take the first floor as the datum; $\hat{K}\dot{E} = \frac{1}{2} \dot{V}^2$, $\hat{P}\dot{E} = gh$

$$\hat{P}\dot{E}_1 = 0$$

$$\hat{K}\dot{E}_1 = \frac{1}{2} \left(\frac{60}{60} \right)^2 = 0.5 \text{ ft}^2/\text{s}$$

(continued)

$$\widehat{PE}_2 = \frac{32.2 \text{ ft}}{\text{s}^2} \left| \frac{30 \text{ ft}}{1} \right| = 965 \frac{\text{ft}^2}{\text{s}^2} \quad \widehat{KE}_2 = \frac{1}{2} \left(\frac{600}{60} \right)^2 = 50.0 \text{ ft}^2/\text{s}^2$$

$$\widehat{PE}_4 = \frac{32.2 \text{ ft}}{\text{s}^2} \left| \frac{60 \text{ ft}}{1} \right| = 1930 \frac{\text{ft}^2}{\text{s}^2} \quad \widehat{KE}_4 = \frac{1}{2} \left(\frac{1200}{60} \right)^2 = 200.0 \text{ ft}^2/\text{s}^2$$

$$\dot{m}_1 = \frac{500 \text{ gal}}{\text{min}} \left| \frac{0.1337 \text{ ft}^3}{1 \text{ gal}} \right| \left| \frac{62.4 \text{ lb}_m}{1 \text{ ft}^3} \right| \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = 69.6 \text{ lb}_m/\text{s}$$

$$\dot{m}_2 = \frac{200 \text{ gal}}{\text{min}} \left| \frac{0.1337 \text{ ft}^3}{1 \text{ gal}} \right| \left| \frac{62.4 \text{ lb}_m}{1 \text{ ft}^3} \right| \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = 27.5 \text{ lb}_m/\text{s}$$

$$\dot{m}_3 = \frac{300 \text{ gal}}{\text{min}} \left| \frac{0.1337 \text{ ft}^3}{1 \text{ gal}} \right| \left| \frac{62.4 \text{ lb}_m}{1 \text{ ft}^3} \right| \left| \frac{1 \text{ min}}{60 \text{ s}} \right| = 41.7 \text{ lb}_m/\text{s}$$

$$\dot{W} = [(200) + 1930] (41.7) + (50 + 96.5) (27.8) - (0.5 + 0)(69.6)]$$

$$\times \frac{(\text{lb}_m)(\text{ft}^2)}{(\text{s})(\text{s}^2)} = 89,000 + 28,200 - 34.8 = 117,170 \frac{(\text{lb}_m)(\text{ft}^2)}{(\text{s})(\text{s}^2)}$$

$$\dot{W} = \frac{117,170 \frac{(\text{lb}_m)(\text{ft}^2)}{(\text{s})(\text{s}^2)}}{32 \frac{(\text{lb}_m)(\text{ft})}{(\text{lb}_f)(\text{s}^2)}} \left| \frac{1}{550(\text{lb}_f)(\text{ft}/\text{s})} \right| = \boxed{6.62 \text{ hp}}$$

27.15

Process: flow System: pump

Basis: 1 kg

Use the steady state mechanical energy balance

$$\Delta(\widehat{KE} + \widehat{PE}) + \int_{p_1}^{p_2} \hat{V} dp - \hat{W} + \hat{E}_v = 0$$

a. $\Delta \widehat{KE} = 0$ Approximately

$$\Delta \widehat{PE} = mgh \left| \frac{1 \text{ kg}}{\text{s}^2} \right| \left| \frac{9.80 \text{ m}}{1} \right| \left| \frac{10 \text{ m}}{1} \right| \left| \frac{1 \text{ J}(\text{s}^2)}{1(\text{kg})(\text{m}^2)} \right| = 98.0 \text{ J}$$

$$\int_{p_1}^{p_2} \hat{V} dp = \hat{V} \Delta p \text{ because } \hat{V} \text{ is essentially constant at } 10^{-3} \text{ m}^3/\text{kg}$$

$$= \frac{10^{-3} \text{ m}^3}{\text{kg}} \left| \frac{(1150 - 101.3) \text{ kN}}{\text{m}^2} \right| \left| \frac{1 \text{ J}}{1(\text{N})(\text{m})} \right| = 1050 \text{ J/kg}$$

$$\hat{E}_v = 60.0 \text{ J/kg}$$

$$\hat{W}_{\text{ideal}} = 98.0 + 1050 + 60.0 = 1208 \text{ J/kg}$$

$$\text{Actual work required} = \frac{1208}{0.70} = \boxed{1726 \text{ J/kg}}$$

Basis: 1 min

(continued)

$$b. \frac{1726 \text{ J}}{\text{kg}} \left| \frac{0.40 \text{ m}^3}{\text{min}} \right| \frac{10^3}{\text{m}^3} = \boxed{6.903 \times 10^3 \text{ J/min}}$$

27.16

The steady state mechanical energy balance is

$$\Delta(\widehat{KE} + \widehat{PE}) + \int \hat{V} dp - \hat{W} + \hat{E}_v = 0$$

System: Pipe above the pump discharge (120 ft long)

Assume

1. $\Delta \widehat{KE} = 0$
2. Discharge pressure is atmospheric so that $p_2 = 0$, and $p_1 = 87.6$ psi
3. $\hat{V}$ is constant at $0.016 \text{ ft}^3/\text{lb}$

Basis: 1 lb water

Then

$\Delta \widehat{PE} = 120(\text{ft})(\text{lb}_f)/\text{lb}_m$. However, the level in discharge tank adds some extra height to 120 ft, say (x) ft

$$\int_{87.6}^0 \hat{V} dp = (0.016)(0 - 87.6)(144) = -201.8(\text{ft})(\text{lb}_f)/\text{lb}_m$$

 $W = 0$ for the system selected

$$\hat{E}_v = -(120 + x) - (-201.8) = 81.8 - x$$

$$\text{The stated value is } \frac{34.6 \text{ lb}_f}{\text{in}^2} \left| \frac{144 \text{ in}^2}{1 \text{ ft}^2} \right| \frac{0.016 \text{ ft}^3}{\text{lb}} = 79.7(\text{ft})(\text{lb}_f)/\text{lb}_m$$

If $x = 2.1$ (ft), then the calculation is ok.

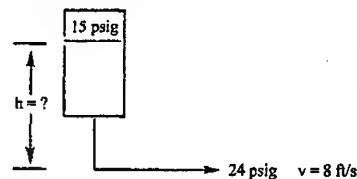
27.17

Assume open, steady state process

The mechanical energy balance is per lb_m

$$\Delta(\widehat{KE} + \widehat{PE}) + \int_{p_1}^{p_2} \hat{V} dp - \hat{W} + \hat{E}_v = 0$$

System: A deareactor plus suction piping to pump

Basis: 1 lb_m

$$\Delta \widehat{KE} = \frac{1}{2} \left(\frac{8 \text{ ft}}{\text{s}^2} \right)^2 \left(\frac{(\text{lb}_f)(\text{s}^2)}{32.2(\text{ft})(\text{lb}_m)} \right) = 0.994(\text{ft})(\text{lb}_f)/\text{lb}_m \text{ (Assumes no velocity in the deareactor)}$$

$$\Delta \widehat{PE} = \left(\frac{32.2 \text{ ft}}{\text{s}^2} \right) \left(\frac{(\text{lb}_f)(\text{s}^2)}{32.2(\text{ft})(\text{lb}_m)} \right) (-h(\text{ft})) = -h(\text{ft})(\text{lb}_f)/\text{lb}_m \text{ (The reference for } h \text{ is at the water level)}$$

(continued)

Solutions Chapter 27

$$\hat{V}\Delta p = \left(\frac{0.016 \text{ ft}^3}{\text{lb}_m} \right) \left(\frac{24-15 \text{ lb}_f}{\text{in}^2} \right) \left(\frac{144 \text{ in}^2}{1 \text{ ft}^2} \right) = 20.77(\text{ft})(\text{lb}_f)/\text{lb}_m$$

$$\dot{W} = 0 \quad \dot{E}_v = 4(\text{ft})(\text{lb}_f)/\text{lb}_m$$

$$-\Delta \widehat{PE} = \Delta \widehat{KE} + \hat{V}\Delta p + E_v$$

$$h = 0.994 + 20.77 + 4 = \boxed{25.8 \text{ ft}}$$

27.18

Basis 1 lb CO₂

The system is the compressor (open, steady state, no reaction). The steady state flow mechanical energy balance reduces to $W = - \int_{p_1}^{p_2} V dp$

Use the CO₂ chart to find the relation between $\hat{V}$ and p .

At the final state the CO₂ is 0.37 gas and 0.63 liquid a.

$\hat{V}(\text{ft}^3/\text{lb}_m)$	$p(\text{psia})$	$\hat{V}(\text{ft}^3/\text{lb}_m)$	$p(\text{psia})$
19.5	6	0.5	220
10	11.5	0.3	330
6	19.5	0.2	460
3	37	0.15	600
1.5	66	0.10	600
1.0	110	0.05	600

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Integrating we get 527

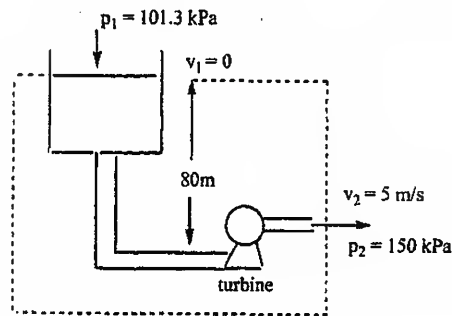
$$\text{b.} \quad -W = \frac{527(\text{ft}^3)(\text{lb}_f)}{(\text{lb}_m)(\text{in}^2)} \left| \frac{144 \text{ in}^2}{\text{ft}^2} \right| \frac{1 \text{ Btu}}{778(\text{ft})(\text{lb}_f)} = \boxed{98 \text{ Btu}/\text{lb}_m}$$

$$\begin{aligned} \text{c.} \quad Q &= \Delta H + W \\ \dot{H}_1 &= 148 \text{ Btu}/\text{lb} & \dot{H}_2 &= 73 \text{ Btu}/\text{lb} \\ Q &= (73-148)-98 = \boxed{-173 \text{ Btu}/\text{lb}} \end{aligned}$$

$$\begin{aligned} \text{d.} \quad \text{Cost} &= \frac{98 \text{ Btu}}{\text{lb}_m} \left| \frac{1}{0.85} \right| \frac{2.93 \times 10^{-4} (\text{kW})(\text{hr})}{1 \text{ Btu}} \left| \frac{\$0.08}{1(\text{kW})(\text{hr})} \right| \\ &= \boxed{\$2.70 \times 10^{-3}} \end{aligned}$$

27.19

Basis: 1 second



$$\Delta \widehat{PE} + \Delta \widehat{KE} + \int_1^2 \hat{V} dp - \dot{W} + \dot{E}_v = 0$$

$$\Delta \widehat{KE} = \frac{1}{2}(v_2^2 - v_1^2) = \frac{1}{2}(5^2 - 0^2) = 12.5 \frac{\text{m}^2}{\text{s}^2} = 12.5 \frac{\text{J}}{\text{kg}}$$

$$\int_1^2 \hat{V} dp = \hat{V}(p_2 - p_1) = 1 \times 10^{-3} \frac{\text{m}^3}{\text{kg}} (150 - 101.3) \text{ kPa} = 48.7 \times 10^{-3} \frac{\text{J}}{\text{kg}} \quad (\text{ignore})$$

$$\Delta \widehat{PE} = gh = 9.8(0 - 80) = -784 \frac{\text{J}}{\text{kg}}$$

$$W_{\text{ideal}} = \frac{W_{\text{actual}}}{\eta_{\text{eff}}} = -\frac{200 \text{ kW}}{0.75} = -266.67 \text{ kW} = -266.67 \frac{\text{kJ}}{\text{s}} \quad \text{work done by system}$$

$$-784 \dot{m} + 12.5 \dot{m} + 266.67 \frac{\text{kJ}}{\text{s}} = 0$$

$$\dot{m} = \frac{266.67 \frac{\text{kJ}}{\text{s}}}{(784 - 12.5) \frac{\text{J}}{\text{kg}}} = \boxed{345.65 \frac{\text{kg}}{\text{s}}}$$

27.20

The Bernoulli equation is

$$\frac{v_1^2}{2g} + \frac{p_1}{\rho} + z_1 = \frac{v_2^2}{2g} + \frac{p_2}{\rho} + z_2 \quad \text{where } \Delta p / \rho = h$$

For continuity flow between sections 1 and 2, $Q_1 = Q_2$

$$A_1 v_1 = A_2 v_2$$

Solving the above two equations, we get

$$Q = \frac{A_1 A_2 \sqrt{2g[(h_1 - h_2) + (z_1 - z_2)]}}{\sqrt{A_1^2 - A_2^2}}$$

$$= \frac{A_1 A_2 \sqrt{2g(H + Z)}}{A_1^2 - A_2^2}$$

$$Q = \frac{A_1 A_2 \sqrt{2g\Delta p}}{\sqrt{A_1^2 - A_2^2}} = C_d A_1 \sqrt{2g\Delta p}$$

where

(continued)

Solutions Chapter 27

$$C_d = \frac{A_2}{\sqrt{A_1^2 - A_2^2}} = \frac{1}{\sqrt{\left(\frac{A_1}{A_2}\right)^2 - 1}}$$

C_d is usually determined by experiment.

27.21

Basis: 1 second

$$Q = C_d A \sqrt{2g(\Delta p + z)} \quad (a)$$

Let $z = 0$.

$$\dot{m} = \frac{Q \text{ m}^3}{\text{s}} \left| \frac{\rho \text{ kg}}{\text{m}^3} \right|$$

Multiply both sides of Equation (a) by ρ

$$\dot{m} = C_d A \sqrt{2g\Delta p \rho^2} \quad (b)$$

The units under the square root are

$$\frac{\text{g(m)}}{\text{s}^2} \left| \frac{\Delta p(\text{m})}{\left(\frac{\text{kg}}{\text{m}^3}\right)^2} \right| \rightarrow \left(\frac{\text{kg}}{\text{s}}\right)^2 \frac{1}{\text{m}^4} \text{ which is ok}$$

If Δp is in the units of Pa

$$\text{Pa} = \frac{\text{N}}{\text{m}^2} = \frac{(\text{kg})(\text{m})}{\text{s}^2} \left| \frac{1}{\text{m}^2} \right|$$

Solutions Chapter 27

$$(\rho)(\Delta p) = \left[\frac{\text{kg}}{\text{m}^3} \right] \left[\frac{(\text{kg})(\text{m})}{(\text{s}^2)(\text{m}^2)} \right] \rightarrow \left(\frac{\text{kg}}{\text{s}} \right)^2 \frac{1}{\text{m}^4} \text{ which is ok}$$

Thus

$$\dot{m} = C_d A \sqrt{2\rho \Delta p} \quad (c)$$

The gas density is

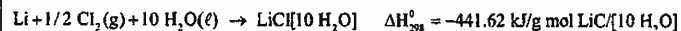
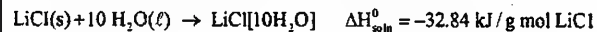
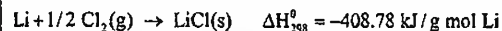
$$\rho = \frac{p}{RT}$$

$$\frac{307 \times 10^3 \text{ Pa}}{82.06 (\text{cm}^3)(\text{atm})} \left| \frac{(\text{g mol})(\text{K})}{303 \text{ K}} \right| \left| \frac{16 \text{ g CH}_4}{1 \text{ g mol CH}_4} \right| \left| \frac{1 \text{ atm}}{101.3 \text{ kPa}} \right| = 1.95 \frac{\text{g}}{\text{cm}^3}$$

$$\dot{m} = \frac{(0.65) \left| \frac{\pi (4 \times 10^{-3} \text{ m})^2}{4} \right| \left[\frac{(2)(1.95 \text{ g})}{(\text{cm}^3)} \left| \frac{1 \text{ kg}}{1000 \text{ g}} \right| \left(\frac{100 \text{ cm}}{1 \text{ m}} \right)^3 \right] \left| \frac{307 - 99 \text{ kPa}}{\text{m}^4} \right|^{1/2}}{1} = 7.36 \times 10^{-3} \text{ kg/s}$$

Solutions Chapter 28

28.1



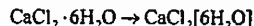
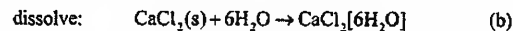
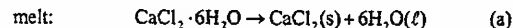
28.2

The reason the freezing works is because heat removed from the ice cream during the solution of the salt (for the $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, the resulting solution is with the attached water of hydration).

Note: A mixture of 3 g of ice to 1 g NaCl is 10 g mol H_2O to 1 g mol of NaCl.
 $\text{NaCl}(\text{s}) + 10 \text{H}_2\text{O} \rightarrow \text{NaCl}[10 \text{H}_2\text{O}]$

$$\Delta H = (-408.99) - (-411.00) = 2.01 \text{ kJ/g mol NaCl}$$

For the $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, you first decompose it and then dissolve it in the H_2O of hydration (it melts in effect).



$$\Delta H_{\text{a}} = [6(-285.840) + 1(-794.97)] - 2586.5 = +76.49 \text{ kJ}$$

$$\Delta H_{\text{b}} = (-854.4) - (-794.97) = -59.40$$

$$\Delta H_{\text{overall}} = 17.06 \text{ kJ}$$

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Salt	$\Delta H_{\text{solution}}^{\circ}$ kJ/g mol	M.W.	$\Delta H_{\text{solution}}$ J/g	Best per mol	Best per g
NaCl	+ 2.01	58.6	+ 34.3		
NH_4Cl	+ 14.10	53.6	+ 263		✓
CaCl_2	- 65.06	111.2	- 585		
$\text{CuCl}_2 \cdot 6\text{H}_2\text{O}$	+ 17.06	219.2	+ 77.8	✓	

28.3

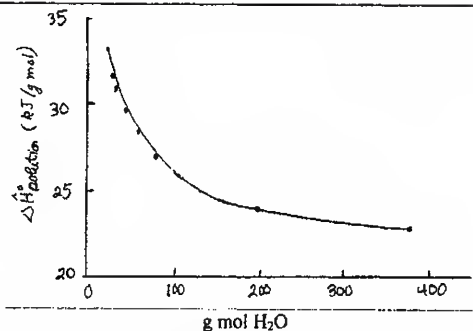
Reference: 25°C and 1 atm for compounds

a. Integral heat of solution for 1 mol Na_2CO_3 (MW = 106.0)

<u>Moles H_2O added</u>	<u>$\Delta H_{\text{f}}^{\circ}$ (J/g mol)</u>	<u>Integral $\Delta H_{\text{solution}}$ (J/g mol)</u>
0	-1130.92	0
15	-1163.70	-32.78
20	-1162.78	-31.86
25	-1161.98	-31.06
40	-1160.22	-29.30
75	-1158.00	-27.01
100	-1157.17	-26.25
200	-1155.50	-24.58
400	-1154.37	-23.45

(continued)

Solutions Chapter 28



b. The initial components are at 25°C. The heat capacity of the solution can be assumed to be that of water (although in Perry, a solution of 4% Na₂CO₃ has a heat capacity of 95% of that of water)

$$C_p = \frac{1 \text{ cal}}{(\text{g})(^\circ\text{C})} \left| \frac{18 \text{ g H}_2\text{O}}{1 \text{ g mol H}_2\text{O}} \right| \frac{4.184 \text{ J}}{1 \text{ cal}} = \frac{75.3 \text{ J}}{(\text{g mol})(^\circ\text{C})} \quad (\text{or } 71.5 \text{ J}/(\text{g mol})(^\circ\text{C}))$$

If the process is batch, assume $\Delta U = \Delta H$.

$$\frac{143 \text{ kg Na}_2\text{CO}_3 \cdot 10 \text{ H}_2\text{O}}{286 \text{ kg Na}_2\text{CO}_3 \cdot 10 \text{ H}_2\text{O}} \left| \frac{1 \text{ kg mol Na}_2\text{CO}_3}{1 \text{ kg mol Na}_2\text{CO}_3 \cdot 10 \text{ H}_2\text{O}} \right| = 0.50 \text{ kg mol Na}_2\text{CO}_3$$

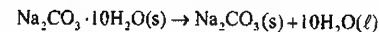
$$\frac{180 \text{ kg H}_2\text{O}}{18 \text{ kg H}_2\text{O}} \left| \frac{1 \text{ kg}}{18 \text{ kg H}_2\text{O}} \right| = 10 \text{ kg mol H}_2\text{O}$$

Basis: 1 g mol Na₂CO₃

The final solution contains 20 kg mol of water and 0.5 kg mol Na₂CO₃ or 40 kg mol H₂O per kg mol of Na₂CO₃. From the table $\Delta \hat{H}^\circ_{f, \text{solution}} = -1160.22 \text{ kJ/g mol Na}_2\text{CO}_3$.

Solutions Chapter 28

First, calculate the ΔH for the dissolution of one gram mole of Na₂CO₃ · 10H₂O



$$\Delta H^\circ (\text{kJ/g mol}): \quad -4081.9 \quad -1130.92 \quad -285.840$$

$$\Delta H^\circ = [(10)(-285.84) + (1)(-1130.92)] - [-4081.9] = +92.58 \text{ kJ}$$

Next dissolve the 1 g mol of Na₂CO₃ into 40 g mol of H₂O

$$\Delta \hat{H}^\circ \text{ Na}_2\text{CO}_3[40 \text{ H}_2\text{O}] = -1160.22 \text{ kJ}$$

$$\Delta \hat{H}^\circ \text{ Na}_2\text{CO}_3[0 \text{ H}_2\text{O}] = -1130.92$$

$$\Delta \hat{H}^\circ_{\text{solution}} = -29.30 \text{ kJ}$$

$$\Delta \hat{H}^\circ_{\text{overall}} = 92.58 - 29.30 = 63.28 \text{ kJ/g mol Na}_2\text{CO}_3$$

$$n = 20 + 0.5 = 20.5 \text{ kg mol}$$

The energy balance is $\Delta H = Q = nC_p\Delta T$:

Basis: 0.50 kg mol Na₂CO₃ · 10 H₂O dissolved (equal to 0.50 g mol Na₂CO₃)

$$(63,280)(500) = (20.5 \times 10^3)(75.3)(T - 25)$$

$$(T - 25) = 20.5$$

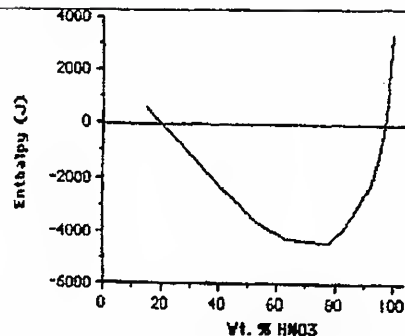
$$T \cong \boxed{45.5^\circ\text{C}} \quad (\text{or } 44.5^\circ\text{C if use } C_p = 71.5)$$

28.4

a.

n_{H_2O} (moles)	ΔH (J)	moles of sol'n	$\Delta H/\text{mol sol'n}$ (J/g mol sol'n)
0.0	3,375	1.0	3,375
0.1	230	1.1	210
0.2	-1,660	1.2	-1,385
0.3	-2,920	1.3	-2,245
0.5	-3,980	1.5	-2,655
0.67	-6,150	1.67	-3,680
1.0	-8,830	2.0	-4,415
1.5	-10,735	2.5	-4,295
2.0	-12,865	3.0	-4,290
3.0	-14,610	4.0	-3,650
4.0	-14,465	5.0	-2,895
5.0	-14,320	6.0	-2,385
10.0	-6,915	11.0	-630
20.0	-12,705	21.0	605

Plot the enthalpy per mole of solution from the table above as a function of the wt. % HNO_3 from the first table.



b. 4 moles H_2O to 4 moles HNO_3 is a 50 mole % solution of acid

33 mole % + 60 mole % $\rightarrow$ 50 mole %

A

B

F

Basis: 8 mol final solution (F)

If the process is batch, assume $\Delta U = \Delta H$.

Overall balance: $A + B = F = 8$

HNO_3 balance: $0.333 A + 0.60 B = 8 (0.50)$

$$0.333 A + 0.60 (8 - A) = 4$$

Solving: $A = 3$ mol (1 mol HNO_3 , 2 mol H_2O)

$B = 5$ mol (3 mol HNO_3 , 2 mol H_2O)

The problem asks for the heat absorber on mixing the two solutions, A and B. The enthalpy data come from the table in the problem statement.

(continued)

Solutions Chapter 28

$$Q = \Delta H = \Delta H_F - (\Delta H_A + \Delta H_B)$$

$$A: \text{ratio is } 2 \text{ mol H}_2\text{O/mol HNO}_3 = -20,290 \text{ J/g mol HNO}_3$$

$$B: \text{ratio is } 0.67 \text{ mol H}_2\text{O/mol HNO}_3 = -10,880 \text{ J/g mol HNO}_3$$

$$F: \text{ratio is } 1 \text{ mol H}_2\text{O/mol HNO}_3 = -14,230 \text{ J/g mol HNO}_3$$

$$Q = (-14,230 \text{ J/g mol HNO}_3) (4 \text{ g mol HNO}_3) - \{(-20,290 \text{ J/g mol HNO}_3)$$

$$(1 \text{ g mol HNO}_3) + (-10,880 \text{ J/g mol HNO}_3) (3 \text{ g mol HNO}_3)\}$$

$$Q = -3,390\text{J}$$

28.5

$$Q = \Delta H^\infty = \Delta H_{\infty 20\% \text{ sol'n}} - \Delta H_{\text{CaCl}_2}$$

a. Conversion of 20 wt % to moles:

Basis: 100 g solution

$$\frac{20 \text{ g CaCl}_2}{111 \text{ g CaCl}_2} \left| \frac{1 \text{ g mol CaCl}_2}{111 \text{ g CaCl}_2} \right| = 0.18 \text{ g mol CaCl}_2$$

$$\frac{80 \text{ g H}_2\text{O}}{18 \text{ g H}_2\text{O}} \left| \frac{1 \text{ g mol H}_2\text{O}}{18 \text{ g H}_2\text{O}} \right| = 4.44 \text{ g mol H}_2\text{O}$$

$$(4.44/0.18) = 24.7 \text{ g mol H}_2\text{O/g mol CaCl}_2$$

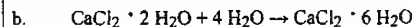
If the process is batch, assume $\Delta U = \Delta H$.

$$\Delta H^\circ = \left(\frac{-208.3 \text{ kcal}}{\text{g mol CaCl}_2} \right) \left(\frac{1 \text{ g mol CaCl}_2}{1} \right) - \left(\frac{190.0 \text{ kcal}}{\text{g mol CaCl}_2} \right) \left(\frac{1 \text{ g mol CaCl}_2}{1} \right) = -18.3 \text{ kcal}$$

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Basis: 1 lb mol CaCl₂

$$Q = \Delta H^\circ = \frac{-18,300 \text{ cal}}{\text{g mol}} \left| \frac{454 \text{ g mol}}{\text{lb mol}} \right| \left| \frac{1 \text{ Btu}}{252 \text{ cal}} \right| = -33,000 \frac{\text{Btu}}{\text{lb mol}}$$



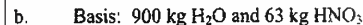
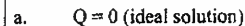
$$\Delta H_{\text{hyd}} = (-623.15) - (-333.5) = -289.5 \frac{\text{kcal}}{\text{g mol CaCl}_2}$$

By linear interpolation: $\Delta H = -209.10 \text{ kcal/g mol CaCl}_2$

$$\Delta H_\infty = (-209.10) - (-208.3) = -0.8 \text{ kcal/g mol CaCl}_2$$

$$Q = \Delta H_\infty = (-800) (1.8) = -1,440 \text{ Btu / lb mol CaCl}_2$$

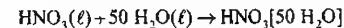
28.6



$$\text{MW: H}_2\text{O} = 18, \text{HNO}_3 = 63.0$$

$$\frac{900}{18} = 50 \text{ kg mol H}_2\text{O} \quad \frac{63.0}{63.0} = 1 \text{ kg mol HNO}_3$$

Reference conditions 25°C and 1 atm

If the process is batch, assume $\Delta U = \Delta H$.

(continued)

Solutions Chapter 28

$$\Delta \hat{H}^{\circ}_{\text{solution}} = (-205.978) 0 - (-173.234) = -32.744 \text{ kJ/kg HNO}_3$$

The energy balance reduces to $Q = \Delta H = \Delta H_{\text{solution}}$

$$Q = (50) (-32.944) = \boxed{-1637.2 \text{ kJ}}$$

28.7

Calculate the initial enthalpy. Use H_2SO_4 enthalpy concentration chart.

Comp. (lb)	% H_2SO_4	kg H_2SO_4	T(°F)	$\Delta \hat{H}$ Btu/lb	$\Delta \hat{H}$ (kJ/kg)	ΔH (kJ)
250	20	50	bp 220	90	209.16	52,290
100	98	98	310 K (98°F)	14	32.54	3,253.6
Total		148				55,543

Final H_2SO_4 concentration in a closed system:

$$\frac{148}{350}(100) = 42.3\%$$

Final specific enthalpy:

$$\frac{55,543 \text{ kJ}}{350 \text{ kg}} \left| \frac{1 \text{ Btu}}{1.055 \text{ kJ}} \right| \frac{0.454 \text{ kg}}{1 \text{ lb}} = 68.3 \text{ Btu/lb}$$

From the chart: $T \cong 242^\circ\text{F} \Rightarrow \boxed{117^\circ\text{C}}$ or $\boxed{390 \text{ K}}$

The composition of the liquid is $\approx \boxed{43 \text{ to } 44\% \text{ H}_2\text{SO}_4}$

If the system is closed, then the final state is two phase

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Let $x = \text{lb of liquid}$ and $(350-x) = \text{lb of steam}$. Steam at 242°F and 1 atm is 1166.2 Btu/lb

$$x(20) + (350-x)(1166.2) = 68.3(350)$$

$$\boxed{x = 335 \text{ lb liquid}} \quad (\text{and } 15 \text{ lb steam})$$

28.8

Assume the system is closed, but $\Delta U = \Delta H$.

Data from the H_2SO_4 enthalpy concentration chart. The initial states are:

Comp.	T(K)	T(°F)	% H_2SO_4	% H_2O	kg H_2SO_4	kg H_2O	$\Delta \hat{H}$ (Btu/lb)	Initial	
								$\Delta \hat{H}$ (J/kg)	ΔH (kJ)
20% H_2SO_4	340	152	20	80	100	400	40	92.9	46,450
96% H_2SO_4	310	96	96	4	288	12	-10	-23.2	-6,960
Steam	400	260	0	100	0	100		2729.7	272,970
Total					388	512		2799.4	312,460

b. The final concentration of the mixture is (total is 900 kg)

$$\% \text{H}_2\text{SO}_4 = \frac{388}{900}(100) = 43\%$$

$$\% \text{H}_2\text{O} = 100 - 43 = 57\%$$

a. The energy balance reduces to $\Delta H = 0$, or $\Delta H_{\text{initial}} = \Delta H_{\text{final}}$. The specific enthalpy of the final solution is $312,460 \text{ kJ}/900 \text{ kg} \approx 347.2 \text{ kJ/kg}$

(continued)

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$$\frac{347.2 \text{ kJ}}{\text{kg}} \left| \frac{1 \text{ Btu}}{1.055 \text{ kJ}} \right| \frac{0.454 \text{ kg}}{1 \text{ lb}} = 135.2 \text{ Btu/lb}$$

From the H_2SO_4 enthalpy - concentration chart for these two conditions,

$$T \cong 251^\circ \text{F} \quad \text{or} \quad \boxed{395 \text{ K}}$$

$$\boxed{122^\circ \text{C}}$$

$$\text{The concentration of the liquid is } \boxed{53\% \text{ H}_2\text{SO}_4}$$

28.9

This problem can be solved using the charts in Appendix I for NH_3 and H_2SO_4 , but the readings will not be very accurate. It is better to go to a reference book (or the internet) to get data for NH_3 , and use Table H1 for H_2SO_4 .

Preliminary calculations for NH_3 :

Basis: 100 g of 15% NH_4OH by weight at 1 atm

	g	MW	g mol
NH_4OH	15	35.05	0.428
H_2O	85	18.02	4.717
Total	100		5.145

	g mol	MW	g
NH_3	0.428	17.03	7.29
H_2O	$0.428 + 4.717 = 5.145$	18.02	92.71
			100.0

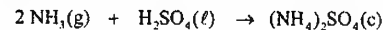
The energy balance will reduce to $Q = \Delta H$ if the system is open and $Q = \Delta U$ if the system is closed, but we can assume for a closed system $\Delta U \cong \Delta H$.

$$\Delta H = \sum_{\text{Products}} \Delta H - \sum_{\text{Reactants}} \Delta H + \Delta H_{\text{rxn}} + \sum_{\text{Solution}} \Delta H$$

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Reference conditions 25°C and 1 atm

ΔH_{rxn} : The reaction is calculated from (on the basis of 0.428 g mol NH_3)



$$\Delta \hat{H}_f^\circ (\text{kJ/g mol}): \quad -46.191 \quad -811.32 \quad -1179.3$$

$$\begin{aligned} \Delta H_{\text{rxn}} &= [0.428(0.5)(-1179.3)] - [(0.428)(-46.191) + (0.428)(0.5)(-811.32)] \\ &= -58.98 \text{ kJ} \end{aligned}$$

The data for NH_3 come from the LaRoche Industries website rather than Appendix I.

$\Delta H_{\text{Products}}$: The products are at the reference conditions so that $\Delta H_{\text{Products}} = 0$.

$\Delta H_{\text{Reactants}}$: The H_2SO_4 is at 25°C and 1 atm, hence its $\Delta H = 0$. The NH_3 is at 1 atm where the temperature is 171°F (77°C). The ΔH from 77°C to 25°C (331 K to 298 K) for a 7.29% (by weight) solution of NH_3 in water requires data for the heat capacity which is not available, hence use the value for the water alone (92.71 g or 0.0927 kg)

Use data from the steam tables or the CD.

$$\Delta H_{\text{NH}_3, \text{soln}} = \frac{0.0927 \text{ kg} \left| \frac{115 \text{ kJ}}{\text{kg}} \right|}{1} = 10.66 \text{ kJ per 100 g NH}_3 \text{ solution}$$

$\Delta H_{\text{Solution}}$ of NH_3 :

Each compound has an associated heat of solution. The values in the LaRoche tables are for 7.2% by weight NH_3 .

(continued)

Solutions Chapter 28

Weight %	T(°F)	T(°C)	ΔH (Btu/lb solution)
7.2	170.8	77	116.1
0	213	100	181.0

The values of ΔH in Btu/lb have to be adjusted to 25°C, and the difference taken. Convert first to kJ.

$$\text{7.29\% solution: } \frac{116.1 \text{ Btu}}{\text{lb solution}} \left| \frac{1.055 \text{ kJ}}{1 \text{ Btu}} \right| \frac{1 \text{ lb}}{0.454 \text{ kg}} = 269.7 \text{ kJ/kg solution}$$

$$\text{0\% solution: } \frac{181.0 \text{ Btu}}{\text{lb solution}} \left| \frac{1.055 \text{ kJ}}{1 \text{ Btu}} \right| \frac{1 \text{ lb}}{0.454 \text{ g}} = 420.61 \text{ kJ/kg solution}$$

Assume you can calculate the ΔH from T to 25°C using only the ΔH of water

$$170.8 - 77 \text{ (92.7\% H}_2\text{O): } \frac{0.0927 \text{ kg}}{100 \text{ g solution}} \left| \frac{219 \text{ kJ}}{\text{kg}} \right| = 20.3 \text{ kJ/100 g solution}$$

$$213 - 77 \text{ (100\% H}_2\text{O): } \frac{0.100 \text{ kg}}{100 \text{ g solution}} \left| \frac{317.7 \text{ kJ}}{\text{kg}} \right| = 31.8 \text{ kJ/100 g solution}$$

$$\text{7.29\% solution: } 26.97 \text{ kJ/100 g solution} - 20.3 \text{ kJ/100 g solution} = 6.67 \text{ kJ/g solution}$$

$$\text{0\% solution: } 42.06 \text{ kJ/100 g solution} - 31.8 \text{ kJ/100 g solution} = 10.26 \text{ kJ/g solution}$$

$$\text{Heat of solution} = 6.67 - 10.26 = -3.59 \text{ kJ/100 g NH}_3 \text{ solution}$$

The g moles of H_2SO_4 needed to react with the 0.428 g mole of NH_3 are $0.5(0.428) = 0.214 \text{ g mol H}_2\text{SO}_4$. The H_2SO_4 solution is 1 mol H_2SO_4 per 3 mol H_2O . From the table in Appendix H, $\Delta H_{\text{solution}} = -48.998 \text{ kJ/g mol H}_2\text{SO}_4$.

$$\Delta H_{\text{solution}} = (-48.998)(0.214) = -10.49 \text{ kJ/100 g NH}_3 \text{ solution}$$

The heat of solution of the $(\text{NH}_4)_2 \text{SO}_4$ in $[5.145 + (3)(0.214)] \text{ mol of H}_2\text{O}$ is not

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known. If the difference between the $\Delta \hat{H}_f^\circ$ of the crystal and aqueous $(\text{NH}_4)_2 \text{SO}_4$ in Appendix F is used, then for $(\text{NH}_4)_2 \text{SO}_4$

$$\Delta H_{\text{solution}} = \frac{[(-1173.1) - (-1179.3) \text{ kJ}]}{\text{g mol}(\text{NH}_4)_2\text{SO}_4} \left| \frac{0.5(0.428) \text{ g mol}(\text{NH}_4)_2\text{SO}_4}{\text{g mol}(\text{NH}_4)_2\text{SO}_4} \right| = 1.33 \text{ kJ per 100 g NH}_3 \text{ solution}$$

$$\Sigma \Delta H_{\text{soln}} = -3.59 - 10.49 + 1.33 = -12.75 \text{ kJ}$$

$$Q = \Delta H = 0 - 10.66 + (-58.98) + (-12.75) = \boxed{-82.39 \text{ kJ}}$$

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28.10

Heat of solution data have been taken from NBS Circular 500.

(a) Basis: 17 lb of NH_3 = 1 lb mol of NH_3

Reference temperature = $77^\circ\text{F} \rightarrow 25^\circ\text{C}$

To convert from kilocalories per gram mole to British thermal units per pound mole, multiply by 1800.

Description	State	$-\Delta\hat{H}_f^\circ$ (kcal/g mol)	$-\Delta\hat{H}_f^\circ$ (Btu/lb mol)	$-\Delta\hat{H}_{\text{soln}}^\circ$ (Btu/lb mol)	Weight % HN_3
$0\text{H}_2\text{O}$	g	11.04	19,900	8,500†	100
$1\text{H}_2\text{O}$	aq	18.1	32,600	12,700	48.5
$2\text{H}_2\text{O}$	aq	18.7	33,600	13,700	32.0
$3\text{H}_2\text{O}$	aq	18.87	34,000	14,100	23.9
$4\text{H}_2\text{O}$	aq	18.99	34,200	14,300	19.1
$5\text{H}_2\text{O}$	aq	19.07	34,350	14,450	15.9
$10\text{H}_2\text{O}$	aq	19.23	34,600	14,700	8.63
$20\text{H}_2\text{O}$	aq	19.27	34,700	14,800	4.51
$30\text{H}_2\text{O}$	aq	19.28	34,700	14,800	3.05
$40\text{H}_2\text{O}$	aq	19.28	34,700	14,800	2.30
$50\text{H}_2\text{O}$	aq	19.29	34,750	14,850	1.85
$100\text{H}_2\text{O}$	aq	19.30	34,750	14,850	0.94
$200\text{H}_2\text{O}$	aq	19.32	34,800	14,900	0.47
$\infty\text{H}_2\text{O}$	aq	19.32	34,800	14,900	0.0

† Represents latent heat of condensation

Standard heats of solution have been calculated from the cumulative data as follows:

$$\Delta\hat{H}_{\text{soln}}^\circ = \Delta\hat{H}_f^\circ - \Delta\hat{H}_{f,\text{gas}}^\circ$$

For example, for $\text{NH}_3[1\text{H}_2\text{O}]$:

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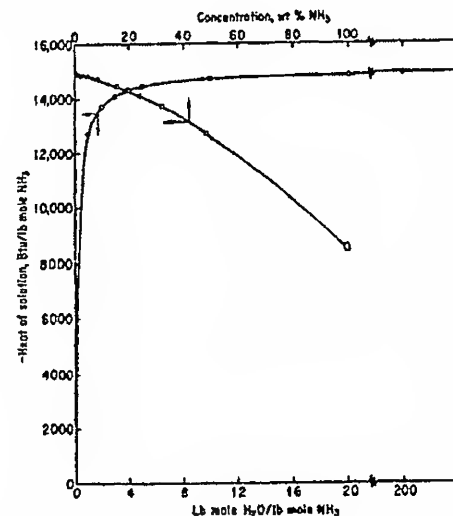
$$\begin{aligned}\Delta\hat{H}_{\text{soln}}^\circ &= -32,600 - (-19,900) \\ &= -12,700 \text{ Btu/lb mol } \text{NH}_3\end{aligned}$$

Weight percents have been computed as follows:

$$\text{wt \% } \text{NH}_3 = \frac{\text{lb } \text{NH}_3 (100)}{\text{lb } \text{H}_2\text{O} + \text{lb } \text{NH}_3}$$

$$\text{wt \% } \text{NH}_3 \text{ for } 1\text{H}_2\text{O} = \frac{17(100)}{18(1) + 17} = 48.5\%$$

The heat of solution values shown in Fig. a are equivalent to the cooling duty required.



(continued)

Solutions Chapter 28

Fig. a.

(b) This part of the problem requires that a new basis be selected, 100 gal of solution. Additional data concerning densities of NH_4OH are shown in the table below. Sample calculations are as follows:

$$\text{density (lb/100 gal)} = \frac{(\text{sp gr soln})(62.4 \text{ lb/ft}^3)(1.003)(100)}{7.48 \text{ gal/ft}^3}$$

Note: 1.003 is the specific gravity of water at 77°F.

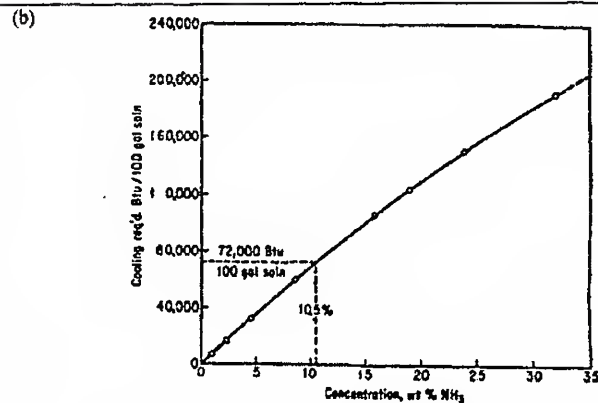
$$\text{density at 32.0\% NH}_3 = \frac{0.889(62.4)(1.003)(100)}{7.48} = 741 \text{ lb/100 gal}$$

$$\text{cooling req'd} \left\{ = \left(\frac{\text{lb mol NH}_3}{100 \text{ gal}} \right) \left(-\Delta H^\circ_{\text{soln}} \frac{\text{Btu}}{\text{lb mol NH}_3} \right) \right.$$

$$\left. \begin{array}{l} \text{cooling req'd} \\ \text{for 100 gal} \\ 32.0 \text{ NH}_3 \text{ soln} \end{array} \right\} = 13.94(13,700) = 191,000 \text{ Btu/100 gal soln}$$

These data are portrayed in Fig. b.

Solutions Chapter 28



Basis: 100 gal of solution at concentrations and densities shown

% NH_3	Sp gr* at 4°C	Density (lb/100 gal)	lb NH_3 100 gal	lb mol NH_3 100 gal	$-\Delta H^\circ_{\text{soln}}$ (Btu/lb mol NH_3)	Cooling Req'd per 100 gal (Btu)
32.0	0.889	741	237	13.94	13,700	191,000
23.9	0.914	761	182	10.70	14,100	151,000
19.1	0.929	774	148	8.70	14,300	124,000
15.9	0.940	784	124.7	7.32	14,400	106,000
8.53	0.965	805	69.4	4.08	14,700	60,000
4.51	0.981	819	37.0	2.18	14,800	32,200
3.05	0.986					
2.10	0.990					
1.85	0.992	826	19.0	1.12	14,800	16,600
0.94	0.995	830	7.8	0.46	14,850	6,900
0.47	0.998					
0.0	1.000	834	0	0	14,900	0

*SOURCE: N. A. Lange, *Handbook of Chemistry*, 8th ed., Handbook Publishers, Sandusky, Ohio, 1958.

(c)

Basis: 100 gal of solution at 10.5% NH_3

$$\Delta E = \Delta U = mC_p \Delta T = mC_p \Delta T = 72,000 \text{ Btu/100 gal}$$

$$\text{sp gr soln} = 0.955$$

(continued)

Solutions Chapter 28

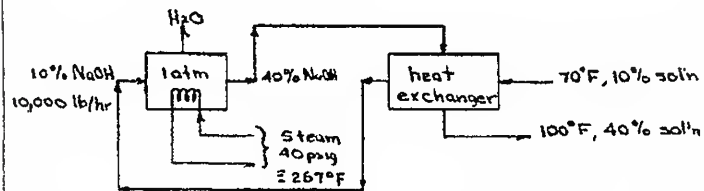
$$m = \frac{0.955(6.24)(1.003)(100)}{7.48} = 800 \text{ lb}$$

$$C_p \text{ 10.5\%NH}_3 \text{ sol'n} = 4.261 \text{ J/(g)}(^{\circ}\text{C}) \\ = 1.02 \text{ Btu/(lb)}(^{\circ}\text{F})$$

$$\Delta T = \frac{\Delta H}{mC_p} = \frac{72,000}{(800)(1.02)} = 88^{\circ}\text{F}$$

$$T_{\text{final}} = 77 + 88 = 165^{\circ}\text{F}$$

28.11



Basis: 1 hour

Open system, steady state

An energy balance shows $Q = \Delta H$.

Enthalpy values from H-x chart for NaOH

Comp.	$\Delta \hat{H}$, Btu/lb sol'n
10% (70°F)	35
40% (100°F)	94
H ₂ O vapor (212°F)	1150

Solutions Chapter 28

$$\frac{10,000 \text{ lb sol'n in}}{100 \text{ lb NaOH}} = \frac{10 \text{ lb NaOH}}{40 \text{ lb NaOH}} = \frac{2500 \text{ lb sol'n out}}{10,000 \text{ lb sol'n in}}$$

$$\text{H}_2\text{O evap} = 7500 \text{ lb}$$

Energy Balance:

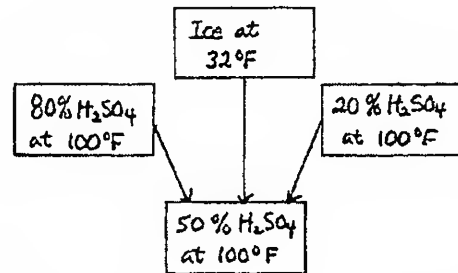
$$Q = 7,500 (1150) + 2500 (94) - 10,000 (35) = 8.515 \times 10^6 \text{ Btu}$$

$$\text{Steam req'd} = Q/\Delta H_{\text{cond.}} = \frac{8.515 \times 10^6 \text{ Btu/hr}}{933.7 \text{ Btu/lb}} = 9140 \text{ lb/hr}$$

28.12

Use the enthalpy concentration diagram for H₂SO₄ (found in Appendix I) for the enthalpy data.

Basis: 1000 lb 50% solution at 100°F



From Appendix I:

(continued)

Solutions Chapter 28

H ₂ SO ₄					
Conc.	temp. (°F)	$\Delta \hat{H}$ (Btu/lb)			
80%	100	-88	$\Delta \hat{H}$ of ice = -144 Btu/lb (or negative of the heat of fusion at 32°F, the reference for the H ₂ SO ₄ chart)		
20%	100	-4			
50%	100	-85			
Assume closed system with $\Delta U = \Delta H$.					
<u>Material Balance:</u>					
Let total lb of 80% H ₂ SO ₄ = x					
Let total lb of 20% H ₂ SO ₄ = y					
Let total lb of ice = z					
<u>Material Balances:</u>					
H ₂ SO ₄ :	0.8x + 0.2y + 0z = 500				
H ₂ O :	0.2x + 0.8y + z = 500				
<u>Energy balance</u> (Q = 0 = $\Delta H = H_{out} - H_{in}$)					
$88x + 4y + 114z = 85,000$					
A summary table can now be completed as follows based on the solution of the three equations using Polymath.					
Component	80% H ₂ SO ₄ (lb)	20% H ₂ SO ₄	Ice (lb)	Final sol'n	Wt.%
H ₂ SO ₄	475	24.6	0	500	50
H ₂ O	119	98.4	282	500	50
Total	594	123	282	1000	100

Solutions Chapter 28

282 lb Ice at 32°F

594 lb 80% H₂SO₄ at 100°F

123 lb 20% H₂SO₄ at 100°F

28.13

The concentration lies on a line joining the coordinates of 0% H₂SO₄, $\Delta H = 1180$, and 30% H₂SO₄ and 70°F. The intersection of this line with the boiling point line = 28%.

28.14

Basis: 1000 lb 10% NaOH at 100°F

a.	Conc.	lb NaOH	lb H ₂ O	total
Initial	10%	100	900	1000
Added	73%	0.73 m	0.27 m	m
Final	30%	100+0.73 m	900+0.27 m	1000 + m

$$\frac{100.0 + 0.73 m}{1000.0 + m} = 0.30$$

$$m = 465 \text{ lb } 73\% \text{ NaOH added}$$

b. Reference State: liquid water at 32°F under its own vapor pressure ($\Delta H = 0$ Btu/lb)

Enthalpy values from NaOH on H-x chart

$$Q = \Delta H = \Delta H_{30\%} - [\Delta H_{10\%} + \Delta H_{73\%}]$$

(continued)

Solutions Chapter 28

Conc.	Temp	lb sol'n	ΔH , Btu/lb	ΔH , Btu
10	100°F	1000	61	61,000
73	200°F	465	371	172,600
30	70°F	1465	37	54,200

$$Q = \Delta H = (54,200) - (61,000 + 172,600) = -179,400 \text{ Btu}$$

$$\text{Heat remove} = 179,400 \text{ Btu}$$

28.15

Basis: 1 hour; Data from $\text{NH}_3 - \text{H}_2\text{O}$ chart

a. Material Balances:

$$\text{Overall: } 10,000 = L + V$$

$$\text{NH}_3: 8,000 = Lx_{\text{NH}_3} + Vy_{\text{NH}_3}$$

$$\text{H}_2\text{O}: 2,000 = Lx_{\text{H}_2\text{O}} + Vy_{\text{H}_2\text{O}}$$

Enthalpy Balance:

$$\Delta H_f = Q = \Delta H_l + \Delta H_v$$

By assuming values of x:

x	y	$\Delta \hat{H}_l$	$\Delta \hat{H}_v$	$(\Delta \hat{H}_v)$ calculated
0.70	0.9993	-31.7	550.7	661.2
0.65	0.9987	-34.1	552.4	508
0.67	0.9989	-33.1	551.8	554

$$x_{\text{NH}_3} = 67\%$$

29.1

a. Dew point = 10°C

$$b. \%RH = \frac{p_{H_2O}}{p_{sat}} 100 = \frac{p_{10^\circ C}}{p_{27^\circ C}} 100 = \frac{1.27 \text{ kPa}}{3.356 \text{ kPa}} 100 = \boxed{38\%}$$

$$c. \mathcal{H} = \frac{p_{H_2O}}{p_{air}} = \frac{1.27}{101.3 - 1.27} \left| \frac{18}{29} \right| = \boxed{0.79 \text{ kg H}_2\text{O/kg air}}$$

29.2

Assume $p_T = 760 \text{ mm Hg}$ a. $p_{H_2O}^* @ 120^\circ F = 87.58 \text{ mm Hg}$

$$\mathcal{H} = \frac{(18)(87.58)}{(29)(672.42)} = \boxed{0.081 \text{ lb H}_2\text{O/lb dry air}}$$

$$b. \hat{V} = [(0.730)(120) + 336] \left(\frac{1}{29} + \frac{0.081}{18} \right) = 16.51 \text{ ft}^3 \text{ at } 120^\circ F \text{ and } 1 \text{ atm}$$

$$c. C_A = 0.240 + 0.45 (0.081) = 0.276 \text{ Btu/(lb dry air)} (^\circ F)$$

29.3

Refer to the text for specific equations and definitions.

29.4

Let A = alcohol and C = CO₂. MW of A = 46; MW of C = 44.At 40°C, $p_A^* = 134.26 \text{ mm Hg}$ or 17.90 kPa

$$a. p_A = 0.10 (100) = 10 \text{ kPa}$$

$$\mathcal{H} = \frac{(46)(10)}{(44)(100 - 10)} = \boxed{0.116 \text{ g A/g C}}$$

$$b. \%RS = \frac{p}{p^*} (100) = \frac{10}{17.90} (100) = \boxed{55.9\%}$$

$$c. C_A = 1.00 + 1.88(\mathcal{H}) = 1.00 + 1.88 (0.116) = 1.22 \text{ J/(K)} (g C)$$

$$d. \hat{V}' = 2.83 \times 10^{-3} T_K + 4.56 \times 10^{-3} (\mathcal{H})$$

$$= (2.80)(10^{-3})(313.15) + (4.56)(10^{-3})(0.116) = \boxed{0.877 \text{ m}^3/\text{kg C}}$$

At saturation at 40°C

$$\mathcal{H} = \frac{(46)(17.90)}{(44)(100 - 17.90)} = \boxed{0.228 \text{ g A/g C}}$$

$$\hat{V}' = (2.80)(10^{-3})(313.15) + 4.56 \times 10^{-3} (0.228) = \boxed{0.878 \text{ m}^3/\text{kg C}}$$

29.5

They are almost parallel to each other.

29.6

When the air is saturated.

29.7

Draw a horizontal line until it intersects with the saturation curve. The temperature at the intersection is the dew-point temperature.

29.8

When the air is saturated (100% relative humidity).

29.9

Condenses water from the air in humid climates.

29.10

The two temperatures are approximately equal at atmospheric temperatures and pressure.

29.11

Because a horizontal line on the psychrometric chart represents a process in which the moisture content (the humidity) constant, and the moisture content of air remains constant during a heating or cooling process.

29.12

$$\text{If by "air" is meant wet air, } H = \frac{0.02}{0.98} = 0.0204 \frac{\text{lb H}_2\text{O}}{\text{lb dry air}}$$

From the SI humidity chart

- Dew point = 25.2°C
- %RH $\cong$ 59%

29.13

- From Humidity Chart, where $t_{DB} = 90^\circ\text{C}$ (194°F) and $t_{WB} = 46^\circ\text{C}$ (115°F) $H = 0.049 \text{ kg H}_2\text{O/kg air}$. Upon cooling to 43°C (109°F), no condensation occurs, therefore H is constant.

$$\frac{0.049 \text{ kg H}_2\text{O}}{1 \text{ kg air}} \left| \frac{29 \text{ kg air}}{1 \text{ kg mol air}} \right| \frac{1 \text{ kg mol H}_2\text{O}}{18 \text{ kg H}_2\text{O}} = \boxed{0.079 \frac{\text{kg mol H}_2\text{O}}{\text{kg mol air}}}$$

$$\text{b. Final pressure} = 100 \left(\frac{273 + 43}{273 + 90} \right) = \boxed{87.1 \text{ kPa}}$$

$$\text{c. At saturation: } 0.079 = \frac{p_{\text{H}_2\text{O}}^*}{87.1 - p_{\text{H}_2\text{O}}^*}; \text{ solving } p_{\text{H}_2\text{O}}^* = 6.38 \text{ kPa}$$

At the dew point, the vapor pressure of pure water is equal to 6.38 kPa. Dew point = $\boxed{37^\circ\text{C} (99^\circ\text{F})}$

The same answer can be obtained by proceeding to the dew point at constant H on a humidity chart for the correct pressure.

29.14

From the SI chart at the intersection of $T_{DB} = 30^\circ\text{C}$ and $\text{RH} = 65\%$

$$\mathcal{H} = 0.0174 \text{ kg H}_2\text{O/kg dry air}$$

29.15

The state in the problem is defined by $T_{DB} = 82^\circ\text{F}$ and $T_{WB} = 70^\circ\text{F}$. The total pressure is 14.696 psia. From the psychrometric chart you can get the necessary values. At the intersection of the DB line and the WB line read:

a. $\mathcal{H} = 0.014 \text{ lb water/lb dry air}$

b. Read: $\text{RH} = 56\%$

c. The vapor pressure of water p_{H_2O} , at 82°F is (from the steam tables) = 0.5409 psia

d. From the humidity chart, the dewpoint is 65°F

e. The enthalpy comes from following the WB line to the left (34.2) less the enthalpy deviation of -0.1 Btu/lb dry air.

$$H \approx 34.1 \text{ Btu/lb dry air}$$

f. The specific volume at the initial point is

$$\sim 14 \text{ ft}^3/\text{lb dry air}$$

29.16

Basis: 1 lb dry air

Data from the humidity chart.

Initial state:

$$T_{DB} = 180^\circ\text{F} \text{ and } T_{WB} = 120^\circ\text{F}$$

$$\mathcal{H} = 0.0637 \text{ lb H}_2\text{O/lb dry air}$$

$$H_{\text{sat}} \approx 120 \text{ Btu/lb dry air}$$

$$\delta H_{\text{deviation}} \approx -1.5 \text{ Btu/lb dry air}$$

$$H = 118.5 \text{ Btu/lb dry air}$$

Final state

$$T_{DB} = 115^\circ\text{F}, \quad T_{WB} = ?, \quad H = 0.0657 \text{ lb H}_2\text{O/lb dry air}$$

$$H_{\text{sat}} \approx 101 \text{ Btu/lb dry air}$$

$$\Delta H = 101 - 118.5 = -17.5 \text{ Btu/lb dry air}$$

29.17

$$\text{State: } T_{DB} = 80^\circ\text{F} \quad \text{RH} = 65\%$$

Basis: 1 lb dry air

$$\mathcal{H} \text{ from the humidity chart is } 0.0142 \text{ lb H}_2\text{O/lb dry air}$$

Solutions Chapter 29

29.18

From the humidity chart

Humidity $\cong 0.0105$ kg/kg dry airWet bulb temperature $\cong 21.5^\circ\text{C}$ Humid volume $\cong 0.88$ m³/kg dry airDew point $\cong 14.7^\circ\text{C}$ Specific enthalpy $\cong 63 - 0.5 \cong 62.5$ kJ/kg dry air

29.19

From the humidity chart

Relative humidity $\cong 30\%$ Specific enthalpy $\cong 76.5 - 0.65 = 75.85$ kJ/kg dry air

29.20

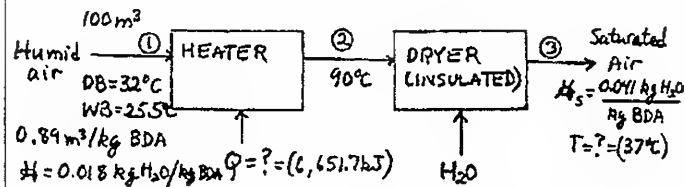
From the humidity chart

Dry bulb temperature $\cong 33.7^\circ\text{C}$ Wet bulb temperature $\cong 27^\circ\text{C}$ Relative humidity $\cong 60\%$ Humid volume $\cong 0.897$ m³/kg dry airEnthalpy $\cong 85.1 - 0.34 = 84.76$ kJ/kg

Solutions Chapter 29

29.21

Basis: 1 lb bone dry air (BDA)

Basis: 100 m³

Data from psychrometric chart (BDA = bone dry air).

a. @ 1, Dew point = 23°C b. @ 1, humidity = $0.018 \text{ kg H}_2\text{O} / \text{kg dry air}$ c. @ 1, Relative humidity = $\frac{H}{H_s} = \frac{0.018}{0.033}(100) = 54.5\%$ d. $\Delta H = Q + W$ $W = 0$

$$Q = \Delta H_2 - \Delta H_1 = (141.5 - 3.6) \frac{\text{kJ}}{\text{kg BDA}} - (79.0 - 0.3) \frac{\text{kJ}}{\text{kg BDA}} = 59.2 \frac{\text{kJ}}{\text{kg BDA}}$$

$$m = \frac{V}{\bar{V}} = \frac{100 \text{ m}^3 \text{ entering air}}{0.89 \text{ m}^3} \frac{\text{kg BDA}}{\text{m}^3} = 112.36 \text{ kg BDA}$$

$$Q = \frac{59.2 \text{ kJ}}{\text{kg BDA}} \left| \frac{112.36 \text{ kg BDA}}{1} \right| = 6,651.7 \text{ kJ}$$

e. Adiabatic cooling by evaporation yields a saturated humidity of 0.041 kg H₂O/kg BDA: (continued)

Solutions Chapter 29

$$\frac{(0.041 - 0.018) \text{ kg H}_2\text{O}}{\text{kg BDA}} \bigg| \frac{112.36 \text{ kg BDA}}{110 \text{ m}^3 \text{ air}} = \frac{2.58 \text{ kg H}_2\text{O}}{100 \text{ m}^3}$$

f. $T_{\text{exit}} = 37^\circ\text{C}$

29.22

Basis: 1 lb dry air

Assume $p_T = 760 \text{ mm Hg}$

a. $p^*_{\text{H}_2\text{O}} @ 120^\circ\text{F} = 87.58 \text{ mm Hg}$

$$H = \frac{(18)(87.58)}{(29)(672.42)} = 0.081 \text{ lb H}_2\text{O} / \text{lb dry air}$$

b. From psychrometric chart, sat'd volume @ $120^\circ\text{F} = 16.52(\text{ft})^3 / \text{lb dry air}$

c. From psychrometric chart, adiabatic cooling temp = wet bulb temp = 77°F

d. $\mathcal{H} @ 120^\circ\text{F}$ (DP = 60°F) = $0.0110 \text{ lb H}_2\text{O} / \text{lb air}$

$$\mathcal{H}_{\text{sat}} @ 82^\circ\text{F} = 0.0237 \text{ lb H}_2\text{O} / \text{lb air}$$

$$\% \text{ sat} = \frac{(0.0110)(100)}{(0.0237)} = 46.7\%$$

e. $H_{\text{sat}} @ 60^\circ\text{F} = 0.01101 \text{ lb H}_2\text{O} / \text{lb dry air}$

$$H_{\text{sat}} @ 40^\circ\text{F} = 0.00515 \text{ lb H}_2\text{O} / \text{lb dry air}$$

$$0.01101 - 0.00515 = 0.00586$$

Solutions Chapter 29

$$\frac{0.00586 \text{ lb H}_2\text{O}}{\text{lb dry air}} \bigg| \frac{98.9 \text{ lb dry air}}{100 \text{ lb moist air}} = \frac{0.579 \text{ lb H}_2\text{O}}{100 \text{ lb moist air}}$$

29.23

From the SI psychrometric chart at 29°C and 40% relative humidity read

$$T_{\text{WB}} = 19.3^\circ\text{C}$$

Assuming the liquid water is supplied at a temperature not much different than the exit temperature of the air stream, the evaporative cooling process follows a line of constant wet-bulb temperature, which is the lowest temperature that can be obtained on an evaporative cooler. That is,

$$T_{\text{min}} = T_{\text{WB}} = 19.3^\circ\text{C}$$

29.24

Excess dryness in the air feels uncomfortable.

29.25

To reduce the relative humidity so the air will not feel so damp.

29.26

Yes.

29.27

a. The humidity of the entering air at 225°F DB and 110°F WB is obtained from the humidity chart.

(continued)

Solutions Chapter 29

$$\text{Humidity} = 0.031 \frac{\text{lb H}_2\text{O}}{\text{lb dry air}}$$

Assume the exit air to be saturated at 125°F.

$$\text{Humidity} = 0.0955 \frac{\text{lb H}_2\text{O}}{\text{lb dry air}}$$

b. Basis: 1 hr

$$\frac{10 \text{ tons}}{\text{day}} \left| \frac{1 \text{ day}}{24 \text{ hr}} \right| \frac{2000 \text{ lb}}{\text{ton}} = 835 \text{ lb/hr}$$

$$\text{Water in} = (0.1)(835) = 83.5 \text{ lb/hr}$$

$$\text{Water out} = \frac{(0.9)(835) \text{ lb dry grain}}{99 \text{ lb dry grain}} \frac{1 \text{ lb H}_2\text{O}}{1 \text{ lb dry grain}} = 7.59 \text{ lb/hr}$$

$$\text{lb H}_2\text{O removed/hr} = \text{water in} - \text{water out} = 83.5 - 7.59 = 75.9 \text{ lb H}_2\text{O/hr}$$

$$\text{c. Product output} = \left[(0.9)(835) \frac{\text{lb dry grain}}{\text{hr}} + 7.59 \frac{\text{lb H}_2\text{O}}{\text{hr}} \right] \left(\frac{24 \text{ hr}}{1 \text{ day}} \right) = 18,200 \text{ lb/day}$$

$$\text{d. } \frac{\text{lb BDA}}{\text{hr}} = \frac{7.59 \text{ lb H}_2\text{O/hr}}{(0.0955 - 0.0310) \text{ lb H}_2\text{O/lb BDA}} = 1175 \text{ lb BDA/hr}$$

$$Q = \Delta H = \text{Enthalpy out} - \text{Enthalpy in}$$

$$= \Delta H_{\text{air}} + \Delta H_{\text{dry grain}} + \Delta H_{\text{water}}$$

$$= 1175 \frac{\text{lb BDA}}{\text{hr}} \left[136.5 \frac{\text{Btu}}{\text{lb BDA}} - (92.25 - 2.25) \frac{\text{Btu}}{\text{lb BDA}} \right]$$

$$+ \frac{(0.9)(835) \text{ lb dry grain}}{\text{hr}} \left| \frac{0.18 \text{ Btu}}{(\text{lb}) (^\circ\text{F})} \right| (110 - 70) ^\circ\text{F}$$

Solutions Chapter 29

$$+ \frac{7.59 \text{ lb H}_2\text{O}}{\text{hr}} \left| \frac{1.0 \text{ Btu}}{(\text{lb}) (^\circ\text{F})} \right| (110 - 32) ^\circ\text{F}$$

$$- \frac{83.5 \text{ lb H}_2\text{O}}{\text{hr}} \left| \frac{1.0 \text{ Btu}}{(\text{lb}) (^\circ\text{F})} \right| (70 - 32) ^\circ\text{F}$$

$$= 5.46 \times 10^4 + 0.54 \times 10^4 + 0.059 \times 10^4 - 0.32 \times 10^4 = 5.74 \times 10^4 \text{ Btu/hr}$$

29.28

Assume in this problem

1. Steady operating conditions
2. Dry air and water vapor are ideal gases
3. $\Delta KE = \Delta PE = W = 0$
4. The mixing is adiabatic ($Q = 0$)

Data from the humidity chart:

Stream 1:

$$H_1 = 110.3 \text{ kJ/kg dry air}$$

$$\mathcal{H} = 0.0272 \text{ kg H}_2\text{O/kg dry air}$$

Stream 2:

$$H_2 = 50.9 \text{ kJ/kg dry air}$$

$$\mathcal{H}_2 = 0.0130 \text{ kg H}_2\text{O/kg dry air}$$

The specific humidity and the enthalpy of the mixture can be determined from mass and energy balances for the adiabatic mixing of the two streams:

Basis: 1 kg dry air

Total Mass balance: $8 + 6 = 14 \text{ kg total}$

(continued)

Solutions Chapter 29

Water mass balance:

$$8(0.0272) + 6(0.0130) = 14 (\mathcal{H}_{\text{mixture}})$$

b. $\mathcal{H} = 0.0211 \text{ kg H}_2\text{O/kg dry air}$

Energy balance ($\Delta H = 0$)

$$8(110.3) + 6(50.9) = 14 (\mathcal{H}_{\text{mixture}})$$

$$\mathcal{H} = 84.8 \text{ kJ/kg dry air}$$

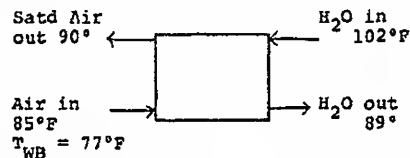
These two properties fix the state of the mixture. Other properties of the mixture are determined from the psychrometric chart.

a. $T = 30.7^\circ\text{C}$

c. $\text{RH} = 75.1\%$

29.29

Data from Humidity Chart



a. $\mathcal{H}_{\text{air in}} = 0.01813 \text{ lb H}_2\text{O} / \text{lb air}$

b. $\mathcal{H}_{\text{air out}} = 0.031 \text{ lb H}_2\text{O} / \text{lb air}$

$$\text{H}_2\text{O picked up} = 0.031 - 0.01813$$

Solutions Chapter 29

$$= 0.0129 \text{ lb H}_2\text{O/lb air}$$

Energy Balance:

$$\Delta H_{\text{air out}} - \Delta H_{\text{air in}} = \Delta H_{\text{water in}} - \Delta H_{\text{water out}}$$

Basis: 1 lb dry air

Ref. temp = 85°F

$$\overbrace{\frac{0.24 \text{ Btu}}{(\text{lb})(^\circ\text{F})} | 1 \text{ lb} | (90-85)}^{\Delta H_{\text{air out}}} + \overbrace{\frac{0.45 \text{ Btu}}{(\text{lb})(^\circ\text{F})} | 0.031 \text{ lb} | (90-85)}^{\Delta H_{\text{H}_2\text{O out}}}$$

$$\overbrace{\frac{+1040 \text{ Btu}}{\text{lb}} | 0.0129 \text{ lb}}^{\Delta H_{\text{H}_2\text{O out}}} \quad \underbrace{-0}_{\Delta H_{\text{air}} + \text{H}_2\text{O in}} \quad \overbrace{\frac{1 \text{ Btu}}{(\text{lb})(^\circ\text{F})} | m \text{ lb} | (102-89)}^{\Delta H_{\text{H}_2\text{O in}} - \Delta H_{\text{H}_2\text{O out}}}$$

$$m = 1.136 \text{ lb H}_2\text{O/lb air or } 0.915 \text{ lb air / lb H}_2\text{O}$$

c. $\% \text{ H}_2\text{O vaporized} = \left(\frac{0.0129}{1.136} \right) 100 = 1.14\%$

29.30

Basis: 180 kg/hr of product

Material Balance

$$\text{Dry product} = \frac{92 \text{ kg dry P}}{100 \text{ kg P}} | \frac{180 \text{ kg P}}{1 \text{ hr}} = 166 \text{ kg dry P/hr}$$

a. Water removed from solid:

(continued)

Solutions Chapter 29

$$\begin{aligned} \ln &= \frac{1.25 \text{ kg H}_2\text{O}}{1.00 \text{ kg dry P}} \left| \frac{166 \text{ kg/hr dry P}}{(0.08)(180) \text{ kg/hr}} \right| - 207.5 \\ &= 207.5 - 14.4 = \boxed{193 \text{ kg H}_2\text{O/hr}} \end{aligned}$$

Basis: 1 BDA

Water picked up in dryer

$$\left(\frac{0.0571 \text{ kg H}_2\text{O}}{\text{kg BDA}} \right)_{\text{out}, 53^\circ} - \left(\frac{0.0083 \text{ kg H}_2\text{O}}{\text{kg BDA}} \right)_{\text{in}, 21^\circ} = 0.0488 \frac{\text{kg H}_2\text{O}}{\text{kg BDA}}$$

$$\frac{\text{kg BDA}}{\text{hr}} = \frac{193 \text{ kg H}_2\text{O}}{0.0488 \text{ kg H}_2\text{O/kg BDA}} = \boxed{3955 \text{ kg BDA/hr}}$$

b. Energy balance

<u>Air:</u>	$\Delta \hat{H}$ (kJ/kg BDA)
air in (21°C, 52% RH):	58.2
air out (53°C, 60% RH):	219.7
$\Delta \hat{H} =$	161.5 kJ/kg BDA

Basis: 1 hr

$$\Delta H = (161.6)(3955) = 6.387 \times 10^5 \text{ kJ}$$

Solid (ref. 21°C)

Solutions Chapter 29

$$\text{solid out: } \Delta \hat{H} = \int_{21}^{43} C_p dT = \left(\frac{0.18 \text{ cal}}{(\text{g})(^\circ\text{C})} \right) \left| \frac{4.184 \text{ J}}{\text{cal}} \right| \left| \frac{10^3}{10^3} \right| (43 - 21)^\circ\text{C} = 16.57 \text{ kJ/kg P}$$

solid in: $\Delta \hat{H} = 0$ (because of reference temperature)

Basis: 1 hr

$$\Delta H = (16.57)(180) = 2983 \text{ kJ}$$

If the dryer and reheater are insulated, then for the system

$$Q - W = \Delta H \quad \text{and} \quad W = 0$$

$$Q_{\text{reheater}} = 2983 + 6.387 \times 10^5 = \boxed{6.42 \times 10^5 \text{ kJ/hr}}$$

29.31

Initial air: $T_{DB} = 38^\circ\text{C}$, $T_{WB} = 27^\circ\text{C}$,

$$H_1 = 0.0175 \text{ kg/kg dry air}$$

Air from scrubber: $T = 24^\circ\text{C}$, $\text{RH} = 100\%$, $\text{RH}_2 = 0.0188 \text{ kg/kg dry air}$ Heated to 93°C : $H_3 = 0.0188$ From drier: $T_{DB} = 49^\circ\text{C}$, $H_4 = 0.0377$ (1000 kg/hr) (0.05) = 50.0 kg H_2O to be evaporated

$$50.0 / (0.0377 - 0.0188) = 2650 \text{ kg dry air/hr}$$

$$2650 (0.0377) = 100 \text{ kg H}_2\text{O/hr}$$

$$V_d \left(\frac{2650}{29} + \frac{100}{18} \right) \left| \frac{22.4}{273} \right| \left| \frac{273 + 49}{273} \right| = 2560 \text{ m}^3 \text{ at } 49^\circ\text{C and 1 atm} \quad (\text{continued})$$

Heat supplied:

$$Q = [(2650)(1.00) + 100(0.200)](93 - 24) = 1.84 \times 10^5 \text{ kJ/hr}$$

Water at 93°C has $p^* = 79.4 \text{ kPa}$

$$H_3 = \frac{(18)}{(29)} \frac{(79.4)}{(101.3 - 79.4)} = 2.25 \text{ kg H}_2\text{O/kg dry air}$$

$$[(0.0188/2.25)](100) = 0.83\% \quad \text{RH air from heater}$$

Answers:

- a. 1. $H = 0.0175$ b. 1. 42% c. 2650 kg dry air/hr
 2. $H = 0.0188$ 2. 100% d. 2560 m^3/hr
 3. $H = 0.0188$ 3. 0.83% e. $1.84 \times 10^5 \text{ kJ/hr}$
 4. $H = 0.0377$ 4. 47%

29.32

Step 5: Basis: 1 hr

Assume:

- $\Delta PE = \Delta KE = W = 0$,
- No reaction occurs,
- open, steady state process,
- ideal gas behavior

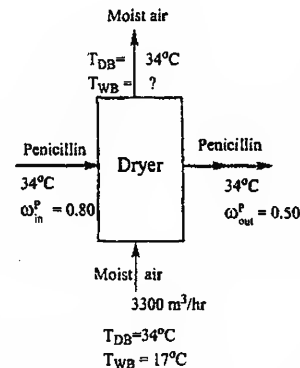
Data:

Entrance air (in)

$\hat{H}$ (kJ/kg dry air)	50.5
$\mathcal{H}$ (kg H ₂ O/kg dry air)	0.00587
$\hat{V}$ (m^3 / kg dry air)	0.88

Assume the properties of the wet penicillin are the same as those of water. ΔH_{vap} at 34°C = 2420.25 kJ/kg water. Let P = kg dry penicillin per hour, and F = kg dry air/hr.

Steps 3 and 4



$$\text{air in} = \frac{4500 \text{ m}^3}{0.88 \text{ m}^3} \frac{1 \text{ kg dry air}}{0.88 \text{ m}^3} = 5114 \text{ kg dry air}$$

Steps 6 and 7:

The exit conditions for the air are not known, but the $\mathcal{H}$ and H are related on the humidity chart hence only one is unknown. P (dry penicillin is unknown).

The balances are water, dry air, and dry penicillin.

Steps 8 and 9

	$T_{\text{wb}} (^{\circ}\text{C})$	$\mathcal{H} \left(\frac{\text{kg H}_2\text{O}}{\text{kg dry air}} \right)$	$\hat{H} (\text{kJ / kg dry air})$
Assume:	20	0.009	57.0
	21	0.010	60.6
	22	0.0115	64.0 (continued)

Water balance:

$$5114 (0.009 - 0.00587) = \text{water evaporated} = 16.0 \text{ kg}$$

$$5114 (0.010 - 0.00587) = 21.1 \text{ kg}$$

$$5114 (0.0115 - 0.00587) = 28.8 \text{ kg}$$

Energy balance:

$$5114 (57.0 - 50.5) / (2420.25) = 13.73 \text{ kg}$$

$$5114 (60.5 - 50.5) / (2420.25) = 21.1 \text{ kg}$$

$$5114 (64.0 - 50.5) / (2420.25) = 28.5 \text{ kg}$$

The solution is very sensitive to the values read from the psychrometric chart. Assume the final $T_{WB} = 21$ or 22°C .

- a. Water evaporated = $\boxed{28.5 \text{ kg}}$
- b. $\Delta H (21^\circ\text{C}) = 51,140 \text{ kJ/kg dry air} \Rightarrow \boxed{51,140 \text{ kJ/hr}}$
- c.

Steps 6 and 7

Unknowns P, exit T_{WB}

Equations air, water

Steps 8 and 9

Water balance on air gives water evaporated $(5114) (0.010 - 0.00587) = 21.1 \text{ kg H}_2\text{O}$

Energy balance: $(60.5 - 50.5) (5114) + 21.1 (2420.25) = 0$

$$0.80 \rightarrow 0.60$$

Use 21°C

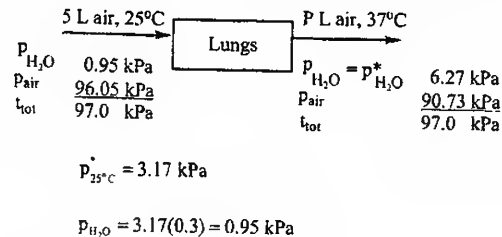
$$21.1 \text{ kg H}_2\text{O evap} = P \left(\frac{0.80}{0.20} - \frac{0.50}{0.50} \right) = 3P$$

$$P = \frac{21.1}{3} = \boxed{7 \text{ kg/hr}}$$

29.33

Steps 1, 2, 3, and 4

The process will be assumed to be a steady state, open, continuous one with 5L flowing in (in the material balance the air is invariant). All of the data for the stream flows and compositions have been placed on the figure. The lungs will be the system.



Step 5: Basis: 5 L air $\rightarrow$ 1 min

Steps 6, 7, 8, and 9:

Material balances

$$\text{In: } n_{\text{air}} = \frac{96.05 \text{ kPa}}{101.3 \text{ kPa}} \left| \frac{1 \text{ atm}}{298 \text{ K}} \right| \frac{5 \text{ L}}{0.08206 (\text{L})(\text{atm})} = 0.194 \text{ g mol}$$

$$n_{\text{H}_2\text{O}} \left(\frac{0.95}{95.05} \right) (0.194) = 1.92 \times 10^{-3} \text{ g mol}$$

Out:

$$n_{\text{air}} = 0.194 \text{ g mol}$$

(continued)

Solutions Chapter 29

$$n_{H_2O} = 0.194 \left(\frac{6.27}{90.73} \right) = 0.0134 \text{ g mol}$$

Energy balance

The energy balance reduces to $Q = \Delta H$. The reference temperature will be 25°C. Assume the increase in water vapor comes from water vaporized at 37°C ($\Delta \hat{H}_{vap} = 2414.3 \text{ kJ/kg}$).

ΔH_{in} : Both the air and water enter at 25°C so $\Delta H = 0$ for both the input streams.

ΔH_{out} :

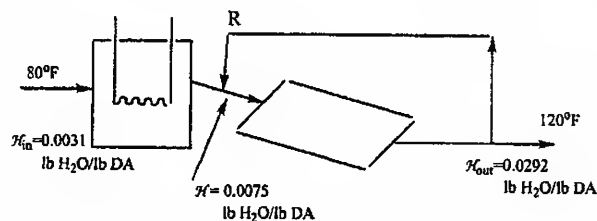
$$\Delta H_{air} = 0.194 \int_{298}^{310} (27.2 + 0.0041 T_K) dT = 66.2 \text{ J}$$

$$\Delta H_{H_2O} = 1.92 \times 10^{-3} \int_{298}^{310} (34.4 + 0.0063 T_K) dT$$

$$+ (0.0134 - 1.92 \times 10^{-3}) (2414.3)(18) = 499 \text{ J}$$

$$Q = \Delta H = 499 + 66.2 = 565 \text{ J/min or } \boxed{33.9 \text{ kJ/hr}}$$

29.34



Basis = 2000 lb dry waste (DW)

Solutions Chapter 29

Comp.	in %	out	waste in =
H ₂ O	63.4	22.7	$\frac{2000}{36.6} \left \frac{0.773}{100} \right \frac{100}{36.6} = 4,220 \text{ lb}$
DW	<u>36.6</u>	<u>77.3</u>	DW out = <u>2,000 lb</u>
	100.0	100.0	H ₂ O evap. = 2,220 lb

Basis: 1 lb dry air

Air in, 80°F, 29.92 in. Hg, and a wet bulb temperature = 54°F:

$$\mathcal{H}_{in} = 0.0031 \text{ lb H}_2\text{O/lb dry air} \quad \hat{H}'_{in} = 22.62 - 0.18 = 22.54 \text{ Btu/lb dry air}$$

Air out, 120°F, 29.92 Hg, and a wet bulb temperature = 94°F:

$$\mathcal{H}_{out} = 0.0292 \text{ lb H}_2\text{O/lb dry air} \quad \hat{H}'_{out} = 61.77 - 0.4 = 61.37 \text{ Btu/lb dry air}$$

Overall

$$\mathcal{H}_{out} = 0.0292 \text{ lb H}_2\text{O/lb dry air}$$

$$\mathcal{H}_{in} = \underline{0.0031}$$

$$\text{H}_2\text{O evaporated} = 0.0261 \text{ lb H}_2\text{O/lb dry air}$$

$$b. \quad \text{air used per ton dust} = \frac{(1 + 0.0031)}{0.0261} \left| \frac{2220}{100} \right| = \boxed{85,400 \text{ lb}} \text{ moist inlet air}$$

per ton DW (continued)

Solutions Chapter 29

$$\text{Air out} = \frac{1.00}{0.0261} \frac{2220}{(29)} = 2,930 \text{ lb mol dry air out}$$

$$\frac{0.0292}{0.0261} \frac{2220}{(18)} = 138 \text{ mol H}_2\text{O out}$$

3068 total mol out

$$c. \quad \frac{3068}{492} \frac{359}{580} = \frac{1,300,000}{1} \text{ ft}^3 \text{ wet air exiting/ton DW}$$

Air Recirculated

R = lb air added at mixing point before kiln

Water balance: $(0.0031)(1) + (0.0292)(W) = (0.0075)(1+W)$

$$0.0292 W = 0.0075$$

$$\frac{-0.0075 W}{0.0217 W} = \frac{-0.0031}{0.0044}$$

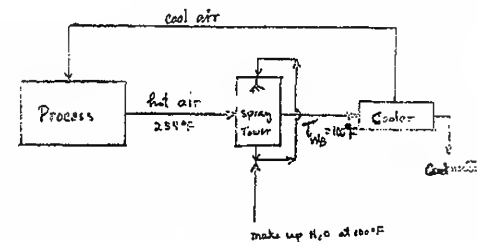
$$0.0217 W = 0.0044$$

$$R = \frac{0.0044}{0.0217} = 0.203 \text{ lb}$$

$$a. \quad \text{Recirculation} = \frac{0.203}{1.203} \frac{100}{1} = 16.8\% \text{ of gas out is recirculated}$$

Solutions Chapter 29

29.35



Adiabatic operation removes 425,000 Btu/hr from the process.

Basis: 1 hr

The energy balance is $\Delta H = 0$ overall.

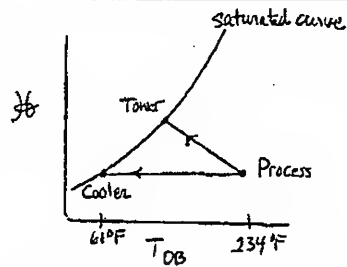
a. For the process:

$$\left. \begin{array}{l} T_{wb} = 100^\circ \text{F} \\ T_{db} = 234^\circ \text{F} \end{array} \right\} RH = 1.3\%$$

b. Temperature leaving the cooler is 61°F (dew point constant W)

c. (continued)

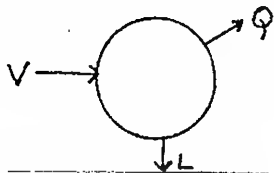
Solutions Chapter 29



d. $\Delta H = (72 - 27) \text{ Btu/lb BDA} = 45$

$$\frac{425,000 \text{ Btu/hr}}{45 \text{ Btu}} = 9450 \text{ BDA/hr}$$

30.1

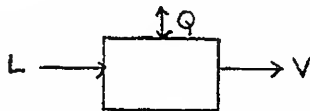


Total variables (2 streams + Q) $2(c+1) + 1 = 2c + 5$

Constraints

indept. material balances		c
energy balance	1	$\frac{c+1}{c+4}$
Net d.f.		

30.2



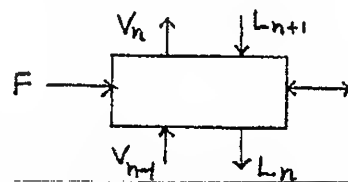
Total variables (2 streams + Q) $2(c+2) + 1 = 2c + 5$

Constraints

indept. material balances		c
energy balance	1	$\frac{c+1}{c+4}$
Net d.f.		

Conventional specifications of variables are the entering stream ($c+2$), and the temperature (1) of the exit stream. In some instances $Q(1)$ may be specified rather than the outlet temperature.

30.3



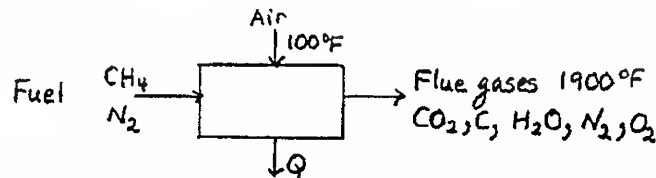
Assume the feed is a single phase stream not the same as any of the other streams.

Total variables (5 streams + Q) $5(c+2) + 1 = 5c + 11$

Constraints:

Indept. material balances	c
Energy balance	1
Equilibrium relations	c
T same in each phase	1
p same in each phase	1
Net d.f.	$\frac{2c+3}{3c+8}$

30.4



The components are 6: CH_4 , CO_2 , CO , H_2O , N_2 , O_2 . Hence, the total no. of variables is for 3 streams + Q

$$3(4+2) + 1 = 19$$

We can reduce these variables by

Note: the true number of phase rule components = 4 (continued)

Solutions Chapter 30

(1)	Material balances (C, H, O, N)	4
(2)	Energy balance	1
(3)	Concentrations of component specified in	
	fuel	3
	air	2
	flue gas	0
(4)	Specification of % excess air (stream flow)	1
(5)	Specification of 3 temperatures	3
		14
		$19 - 14 = 5$

Three pressures must be specified and one extensive variable: feed, air, or flue gas. The last variable would be the ratio of CO to CO₂.

30.5

Each stage has $2c + 6$ variables. Hence, there are $N(2c + 6)$ variables + 1 for the decision as to the value of N . There are $2(N - 1)$ interstreams and thus $2(N - 1)(c + 2)$ restrictions as streams are combined.

$$\text{D.f.} = \{N(2c + 6) + 1\} - \{2(N - 1)(c + 2)\} = 2c + 2N + 5$$

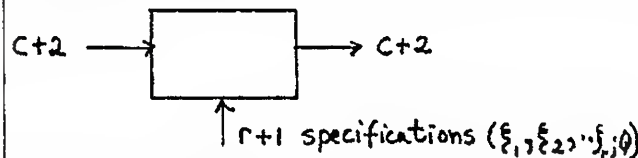
The variables to be specified might be

pressure in each stage	N
Q in each stage	N
F in each stage	$c + 2$
S in each stage	$c + 2$
N in each stage	1
	$\hline 2N + 2c + 5$

Solutions Chapter 30

30.6

Assume phase equilibrium exists, if more than one phase occurs. With r reactions, we have $\xi_1, \xi_2, \dots, \xi_r$ values specified.



We trade r equilibrium relations for the r extent of reactions, and the degrees of freedom are $C + 2 - (r + 1) = C - r + 1$

30.7

24 variables - (3) (5) equations = 9 less 4 specifications
= 5 more specifications
(the equations are energy, mass, equilibria.)

30.8

- a. A set of differential equation can be written for each stage for each component (and total material).

For the steady state, you can write overall balances
total mass balance
NH₃ balance
H₂O balance
sum of mass fraction balances for F, D, B

If a basis is picked, such as $F = 100$, 2 unknowns exist, D and B, and two independent equations exist; hence the system is determinate. (continued)

Solutions Chapter 30

For the sequence of stages, each stage would have:

total material balance
component material balances
equilibrium relations
sum of mass (mole) fraction relations

In total, there would be 6 independent equations and 8 unknown variables on the top stage. The bottom stage would have 7 independent equations and 7 unknowns. Starting at the bottom, each successive stage would be determinate until the top was reached. Without equilibrium relations holding and without knowing enthalpies as a function of concentration, the number of unknowns would exceed the number of independent equations.

- b. Examine unit 1 in as much as no feedback of information occurs. If unit 1 is not determinate, the entire system will not be determinate. The balances for unit 1 are

total
alcohol
inerts
equilibrium
 $y_{10} + y_{10} = 0.90$

} 4 independent equations

The unknowns are 5

$V_1, L_1, S_0, y_{10}, y_{1a}$

Thus, the subsystem is not determinate.

30.9

$$N_v = 3(5 + 2)$$

21

N_r :

Material balances 5

Vapor-liquid equilibria relations 4

(One pair, $x_{35} = K_{5x25}$, is known

(continued)

Solutions Chapter 30

and redundant.)

T's and p's are equal 4

Specified values of variables

($F_1, x_{11}, x_{12}, x_{13}, x_{14}, T, p$) 7 20

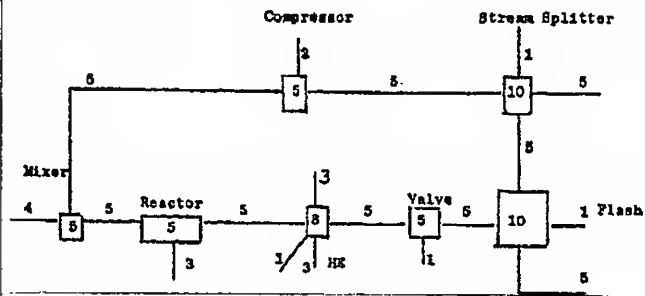
1 = d.f. (under specified)

30.10

Four of the material balance equations are redundant (3 or 13, 8 or 12, 9 or 16, 14, or 15), hence there are 27 independent equations and 34 variables yielding 7 degrees of freedom. Certain of the process variables must be specified, namely the temperatures of the entering streams (T_1, T_4 and T_6), and the flow rate and composition of the exit stream which must meet preset values thus fixing the values of $F_7, x_{1,7}, x_{2,7}, x_{3,7}$ and $x_{4,7}$. However, only three of these four exit mole fractions are independent (because the summation of mole fraction must be unity) and may be specified. Therefore, all of the 7 degrees of freedom are absorbed by the specifications. Thus the problem is properly specified, and can be solved by one of the techniques cited in Appendix L given a set of values for the coefficients C_i, A, U , and p_i plus the values of the 7 specified variables

30.11

Refer to the literature for the analysis. See R.H. Cavett, *Proceed. Am. Petrol. Inst.* 43, 57 (1963).



Basic Block Diagram for the Flowsheet

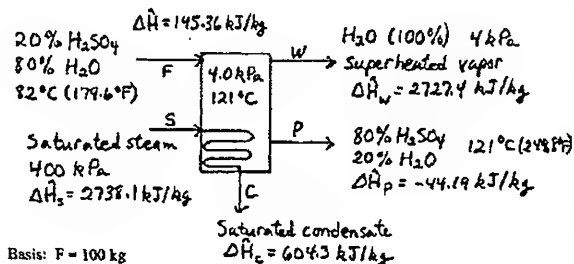
<u>Unit</u>	<u>Equations</u>	<u>Stream Variables</u>	<u>Unit Parameters</u>
Mixer	5	9	0
Reactor	5	5	3
Cooler	8	8	1
Valve	5	5	1
Flash	10	5	1
Bleed	10	5	1
Compressor	5	5	2

<u>Streams Leaving</u>	<u>Stream variables</u>
Cooling Water	3
Product	5
Bleed Stream	5

Total Variables	64
-----------------	----

The flowsheet has

$64 - 48 = 16$ degrees of freedom



Basis: $F = 100 \text{ kg}$

Data

W (interpolating from SI steam tables)

$$\Delta H_v = 2644.0 \frac{\text{kJ}}{\text{kg}} + \frac{(2738.8 - 2644.0) \frac{\text{kJ}}{\text{kg}} (394 - 350) \text{K}}{(400 - 350) \text{K}} = 2727.4 \frac{\text{kJ}}{\text{kg}}$$

F

$$\Delta H = \frac{62.5 \text{ Btu}}{\text{lb}} \left| \frac{1.055 \text{ kJ}}{\text{Btu}} \right| \left| \frac{1 \text{ lb}}{0.4536 \text{ kg}} \right| = 145.36 \frac{\text{kJ}}{\text{kg}}$$

P

$$\Delta H = \frac{-19.0 \text{ Btu}}{\text{lb}} \left| \frac{1.055 \text{ kJ}}{\text{Btu}} \right| \frac{1 \text{ lb}}{0.4536 \text{ kg}} = -44.19 \frac{\text{kJ}}{\text{kg}}$$

Unknowns: $W, P, S = C$

Balances: H_2SO_4 , H_2O (or overall), energy

$$\frac{\text{F kg Feed}}{100 \text{ kg Feed}} = \frac{\text{P kg Product}}{100 \text{ kg Product}}$$

$$0.2 (100 \text{ kg}) = 0.8 P$$

$P = 25 \text{ kg}$

Overall Mass Balance:

$$F_{\text{kg feed}} + S_{\text{kg steam}} = W_{\text{kg vapor}} + P_{\text{kg product}} + C_{\text{kg condensate}}$$

$$F + S = W + P + C$$

$$\mathbf{F} = \mathbf{W} + \mathbf{P}$$

$$(100 \text{ kg}) = W + 25 \text{ kg} \text{ hence } W = 75 \text{ kg H}_2\text{O vapor}$$

Overall Energy Balance Reduces to (Open System, Steady State):

$$\Delta H = 0$$

$$m(\Delta H_C - \Delta H_S) + (m_W \Delta H_W + m_D \Delta H_D - m_F H_F) = 0$$

$$\frac{m(604.3 - 2738.1) \text{ kJ}}{\text{kg}} + \frac{75 \text{ kg}}{\text{kg}} \frac{2727.4 \text{ kJ}}{\text{kg}} + \frac{25 \text{ kg}}{\text{kg}} \frac{-44.19 \text{ kJ}}{\text{kg}} - \frac{100 \text{ kg}}{\text{kg}} \frac{145.36 \text{ kJ}}{\text{kg}} = 0$$

$$-2,133.8 \text{ m kJ/kg} + 204,555 \text{ kJ} - 1,104.75 \text{ kJ} - 14,536 \text{ kJ} = 0$$

$$m = \frac{188,914.751 \text{ kJ}}{88.5 \text{ kg steam}} \left| \frac{100.0 \text{ kg feed}}{88.5 \text{ kg steam}} \right| = 1,129.5 \text{ kg feed}$$

31.2

$$T_3 = 109.34^\circ\text{F}$$

$$T_4 = 86.44^{\circ}\text{C}$$

(continued)

Solutions Chapter 31

F ₃	Components	lb mol/hr
	A	143.01
	B	58.78
	C	35.78

31.3

Basis: 1 hr

Eqn. No.

- (1) Turbine Material Balance

$$A = B + C$$

- (2) Turbine Energy Balance

$$200,000 = \frac{1482A - 1406B - 1164C}{\text{hr}} \left| \frac{1 \text{ hp}}{2.55 \times 10^3 \text{ Btu/hr}} \right.$$

$$20,000 = (B/30) + (C/8)$$

- (3) 600-psi Material Balance

$$B = 100,000 + 100,000 + D + 30,000$$

$$B = D + 230,000$$

- (4) 50-psi Material Balance

$$F + D + 30,000 = E$$

- (5) 50-psi Energy Balance

Solutions Chapter 31

$$1,380 D + 30,000 (1,300) + 218 F = 1,210 E$$

- (6) Deaerator Material Balance

$$E + C + 200,000 = A + F$$

- (7) Deaerator Energy Balance

$$1,210 E + 68 (C + 200,000) = 218 (A + F)$$

There are 7 eqns. and 6 unknowns.

$$\text{Combine (4) \& (6): } A - C - D = 230,000 \quad (8)$$

$$\text{" (4) \& (7): } 218 A - 68 C - 218 D - 992 E = 20,140,000 \quad (9)$$

$$\text{" (4) \& (5): } 1162 D + 32,460,000 = 992 E \quad (10)$$

$$\text{Combine (8) \& (1): } B - D = 230,000 \quad (11)$$

$$\text{" (9) \& (1): } 218 (B + C) - 68 C - 218 D - 992 E = 20,140,000 \quad (12)$$

$$\text{" (10) \& (12): } 218 B + 150 C - 1380 D = 52,600,000 \quad (13)$$

Solving eqns. (2), (11) & (13) simultaneously:

$$B = 240,266 \text{ lb/hr}$$

$$C = 95,929 \text{ lb/hr}$$

$$D = 10,266 \text{ lb/hr}$$

Substituting D in eqn. 10:

$$E = 44,747 \text{ lb/hr}$$

$$\text{" D \& E in eqn. 4: } F = 4,481 \text{ lb/hr}$$

$$\text{" B \& C in eqn. 1: } A = 336,195 \text{ lb/hr}$$

31.4

A calciner presents a classic choice between air preheat and waste-heat boilers. The goal is to reduce the consumption of natural gas. Only about the 50×10^6 Btu/hr are being absorbed into the process. A rough calculation gives

		(Btu/hr)(10^{-6})
Feed heating:	$200,000 \times 0.5 \times (500 - 200)^\circ\text{F}$	= 25
Water vaporization:	$20,000 \times 970$	= 19.4
Water heating:	$20,000 \times 0.5 \times (1,000 - 500)$	= 5.0
Total		49.4

About 150×10^6 are available in the fuel.

Preheating the air

Preheating the air to 560°F will cool the flue gas to about 500°F , and no condensation should occur. The duty of the preheater would be $400,000 \times 0.24 (560 - 60) = 48$ million Btu/hr. The exhaust flue gas from the air preheater could be used to generate steam or to preheat feed (in a direct-contact fluid bed, for example), and the product solids might also be put to use. Either holds the potential for another 20 million Btu/hr savings if a sue can be found for the recovered steam or heat.

Waste heat boiler

About 52,000 lb/hr of 630-psig steam could be generated. This could be used to preheat the feed and perhaps do some of the water vaporization, but his amounts to replacing the calciner--a high-capital-cost route. The steam could also be used to preheat the combustion air to about 450°F . This would utilize $400,000 \times 0.24 \times (450 - 60) = 37.4$ million Btu/hr.

Capital costs of the respective equipment must be considered. Usually the capital cost for air preheat systems are less. In addition, credits are surer, since fuel is conserved directly. The value of the heat saved does not depend on the overall site steam balance. On the other hand, steam is more flexible and far more portable than large volumes of hot gas. Preheated combustion air changes the combustion characteristics and the radiant-heat distribution of a furnace and can increase emissions of nitrogen oxides. The addition

of hot-air ducts can sometimes cause access problems under a furnace and may in fact become uneconomical for furnaces with a large number of wall burners.

31.5

Basis: 1 g mol CaCO_3

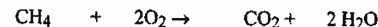


$$\Delta \hat{H}_f^\circ \left(\frac{\text{kJ}}{\text{mol}} \right) \quad -288.45 \quad -151.9 \quad -94.052$$

$$\Delta \hat{H}^\circ_{\text{Rxn}} = 1(-151.9) + 1(-94.052) - 1(-288.45) = 42.50 \text{ kJ/g mol CaCO}_3$$

$$= 177.8 \text{ kJ/g mol}$$

Basis: 1 g mol CH_4



$$\Delta \hat{H}_f^\circ \left(\frac{\text{kJ}}{\text{mol}} \right) \quad -212.80 \quad 0 \quad 0 \quad 0$$

$$\Delta \hat{H}^\circ_{\text{Rxn}} = -[-(-212.80)] = -212.80 \text{ kJ/g mol CH}_4$$

$$= -890.36 \text{ kJ/g mol}$$



Energy balance:

$$Q + W = -\Delta H \text{ or } \Delta H = 0 \quad \text{Ref. } T = 25^\circ\text{C} \quad Q = 0, W = 0$$

(continued)

Basis: 1 g mol CaCO_3

$$\Delta H_{\text{CaO}} = \frac{111 \text{ J}}{(\text{g mol})(^\circ\text{C})} \left| \frac{(900-25)^\circ\text{C}}{1} \right| = 97.125 \text{ kJ/g mol CaO}$$

Let X be the g mol CH_4 /g mol CaCO_3 CaO gases CaCO_3 gas air Reactions

$$[(1)(97.125) + 0] - [0 + 0 + 0] + [(1)(177.8) + X(-890.36)] = 0$$

$$X = 0.309 \text{ g mol CH}_4/\text{g mol CaCO}_3$$

$$\frac{1 \text{ g mol CaCO}_3}{0.309 \text{ g mol CH}_4} \left| \frac{100 \text{ g CaCO}_3}{1 \text{ g mol CaCO}_3} \right| \left| \frac{1 \text{ g mol CH}_4}{16 \text{ g CH}_4} \right| \frac{10^3}{10^3} = 20.2 \frac{\text{kg CaCO}_3}{\text{kg CH}_4}$$

31.6

Basis: 1 hr

Material balance

In	lb	Out	
	lb		
Salt (16,000) (.07)	= 1,120	Salt	= 1,120
Water 16,000 - 1,120	= 14,880	Water soln $1,120 - \frac{1,120}{0.4}$	= 1,680
		Water evap. 14,880 - 1,680	= 13,200

(a) Energy balance Basis: 180°F, liq. H_2O

$$\begin{array}{l} \text{In} \qquad \qquad \qquad \text{Btu} \\ 7\% \text{ Solution} = (0.92)(16,000)(T-180) = 14,720(T-180) \end{array}$$

$$\text{Steam } \Delta H_{\text{vap}} = (15,000)(959) = 14,400,000$$

$$\text{Liq. H}_2\text{O} = (15,000)(1.0)(230-180) = 750,000$$

$$15,150,000 + 14,720(T-180)$$

Out

$$\text{H}_2\text{O vapor } \Delta H_{\text{vap}} = (13,200)(990) = 13,070,000$$

$$\text{Condensate} = 15,000(230-180) = 750,000$$

$$\text{Conc. salt soln} = \underline{\quad 0 \quad}$$

$$13,820,000$$

$$15,150,000 + 14,720(T-180) = 13,820,000$$

$$T = 90^\circ\text{F}$$

The above analysis ignores the heat of solution effects as the NaCl becomes more concentrated.

(b) 2,800 lb 40% NaCl produced/hr

Phase I: Material Balances

Basis: 10,000 lb/hr of mash

(a) Material balance around column I and condenser:

$$\begin{array}{lcl} \text{Feed} & \left\{ \begin{array}{l} A \\ H_2O \\ M \end{array} \right. & \begin{array}{l} \text{In} \\ (0.10)(10,000) = 1,000 \text{ lb} \\ (0.80)(10,000) = 8,000 \text{ lb} \\ (0.10)(10,000) = 1,000 \text{ lb} \end{array} \end{array}$$

10,000 lb

$$\begin{array}{lcl} \text{Product} & \left\{ \begin{array}{l} A \\ H_2O \\ M \end{array} \right. & \begin{array}{l} \text{Out} \\ (1000)(0.667) = 667 \text{ lb} \\ (8000 - 667) = 7,333 \text{ lb} \\ = 1,000 \text{ lb} \\ \hline 10,000 \text{ lb} \end{array} \end{array}$$

(b) Material balance around column I only:

$$\begin{array}{lcl} \text{Feed} & \left\{ \begin{array}{l} A \\ H_2O \\ M \end{array} \right. & \begin{array}{l} = 1,000 \text{ lb} \\ = 8,000 \text{ lb} \\ = 1,000 \text{ lb} \end{array} \\ \text{Reflux} & \left\{ \begin{array}{l} A \\ H_2O \end{array} \right. & \begin{array}{l} (3)(1000) = 3,000 \text{ lb} \\ (3)(667) = 2,000 \text{ lb} \\ \hline 15,000 \text{ lb} \end{array} \end{array}$$

$$\begin{array}{lcl} \text{Overhead vapor} & \left\{ \begin{array}{l} A \\ H_2O \end{array} \right. & \begin{array}{l} (4)(1000) = 4,000 \text{ lb} \\ (4)(667) = 2,667 \text{ lb} \end{array} \\ \text{Bottoms} & \left\{ \begin{array}{l} H_2O \\ M \end{array} \right. & \begin{array}{l} = 7,333 \text{ lb} \\ = 1,000 \text{ lb} \\ \hline 15,000 \text{ lb} \end{array} \end{array}$$

(c) Material balance around column II and condenser:

$$\begin{array}{lcl} \text{Feed} & \left\{ \begin{array}{l} A \\ H_2O \end{array} \right. & \begin{array}{l} = 1,000 \text{ lb} \\ = 667 \text{ lb} \end{array} \end{array}$$

1,667 lb

$$\begin{array}{lcl} \text{(d) Overhead product} & \left\{ \begin{array}{l} A \\ H_2O \end{array} \right. & \begin{array}{l} = 1,000 \text{ lb} \\ (1000 - 1000) = 0 \end{array} \\ \text{Bottoms} & \left\{ \begin{array}{l} H_2O \end{array} \right. & \begin{array}{l} (667 - 50) = 617 \text{ lb} \\ \hline 1,667 \text{ lb} \end{array} \end{array}$$

(d) Material balance on column II cutting reflux and overhead vapor:

$$\begin{array}{lcl} \text{Feed} & \left\{ \begin{array}{l} A \\ H_2O \end{array} \right. & \begin{array}{l} = 1,000 \text{ lb} \\ = 667 \text{ lb} \end{array} \\ \text{Reflux} & \left\{ \begin{array}{l} A \\ H_2O \end{array} \right. & \begin{array}{l} (3)(1000) = 3,000 \text{ lb} \\ (3)(50) = 150 \text{ lb} \\ \hline 4,817 \text{ lb} \end{array} \end{array}$$

$$\begin{array}{lcl} \text{Vapor} & \left\{ \begin{array}{l} A \\ H_2O \end{array} \right. & \begin{array}{l} (4)(1000) = 4,000 \text{ lb} \\ (4)(50) = 200 \text{ lb} \end{array} \\ \text{Bottoms} & \left\{ \begin{array}{l} H_2O \end{array} \right. & \begin{array}{l} (667 - 50) = 617 \text{ lb} \\ \hline 4,817 \text{ lb} \end{array} \end{array}$$

Energy balance around heat exchanger I outlet and overhead vapor and reflux from II:

Reference temperature = 172°F

$$\begin{array}{lcl} \text{Feed to II} & \begin{array}{l} \text{In} \\ 1667(0.85)(176 - 172) = 5,650 \\ \Delta H_{\text{vaporization steam at } 176^\circ\text{F}} \\ + 1667(675) = 1,125,000 \\ \text{Reflux} \quad 3150(0.72)(160 - 172) = -27,200 \\ \text{Steam} \end{array} & \begin{array}{l} \Delta H_{S_1} \\ \Delta H_{S_2} + 1,103,450 \\ \hline \Delta H_{S_1} + 1,103,450 = 2,748,400 \\ \Delta H_{S_2} = 1,645,000 \text{ Btu/hr} \end{array} \\ \text{Vapor} & \begin{array}{l} \text{Out} \\ 4200(0.72)(172 - 172) + 4200(650) = 2,725,000 \end{array} & \\ \text{Bottoms} & 617(1.0)(210 - 172) = 23,400 & \\ \hline & & 2,748,400 \end{array}$$

Total energy input into system:

$$\Delta H_{S_1} + \Delta H_{S_2} + \text{steam heater} = 4,842,000 + 1,645,000 + 1,125,000 = 7,612,000 \text{ Btu/hr} \leftarrow \text{c}$$

Energy balance on condenser I:

W = lb H₂O/hr; Reference temperature = 176°F

$$\begin{array}{lcl} \text{In} & & \text{Out} \\ 6667(0.85)(176 - 176) + (6667)(675) = 4,500,000 & \text{Condensate} & 6667(0.85)(176 - 176) = 0 \\ 18 \text{ H}_2\text{O} \quad W(1.0)(80 - 176) = -96W & \text{Cooling H}_2\text{O} & W(1.0)(130 - 176) = -46W \\ \hline -96W + 4,500,000 & & \hline \end{array}$$

$$50W = 4,500,000 \quad \text{or} \quad W = \frac{4,500,000}{50} = 90,000 \text{ lb H}_2\text{O/hr}$$

$$\frac{90,000 \text{ lb H}_2\text{O/hr}}{8.345 \text{ lb/gal}} = 10,800 \text{ gal H}_2\text{O/hr} \leftarrow \text{d}_1$$

inice on condenser II:

$W = 1\text{ lb H}_2\text{O/hr}$; Reference temperature = 172°F

<i>In</i>		<i>Out</i>	
4200(0.72)(172 - 172) + (4200)(650) =	2,725,000	Condensate 4200(0.72)(160 - 172) =	-36,000
$W(1.0)(80 - 172) =$	-92W	Cooling H ₂ O $W(1.0)(172 - 130) =$	-42W
	<u>-92W + 2,725,000</u>		<u>-42W - 36,000</u>

$$50W = 2,761,000 \quad \text{or} \quad W = \frac{2,761,000}{50} = 55,200 \text{ lb H}_2\text{O/hr}$$

$$\frac{55,200 \text{ lb H}_2\text{O}}{8.345 \text{ lb/gal}} = 6620 \text{ gal H}_2\text{O/hr} \leftarrow (d_2)$$

ance on heat exchanger II:

$$W = 1 \text{ lb H}_2\text{O/hr}; \quad \text{Reference temperature} = 80^\circ\text{F}$$

<i>In</i>		<i>Out</i>	
1050(0.72)(160 - 80)	= 60,500	Product	1050(0.72)(100 - 80) = 15,120
$W(1.0)(80 - 80)$	= 0	Cooling H ₂ O	$W(1.0)(130 - 80) = 50W$
	<u>60,500</u>		<u>50W + 15,120</u>

$$50W + 15,120 = 60,500$$

$$W = 907 \text{ lb H}_2\text{O/hr} \quad \text{or} \quad 109 \text{ gal H}_2\text{O/hr} \leftarrow (d_3)$$

Phase 2: Energy Balances

(a) *Energy balance on heat exchanger III (Fig. ES.15b):*

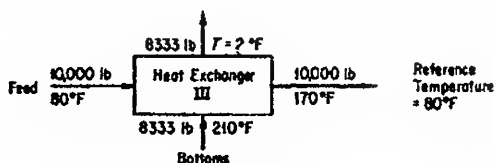


Fig. E5.15b

$$\begin{array}{rcll} \text{Feed} & (10,000)(0.96)(80 - 80) = & 0 \text{ Btu} & \text{Feed} & (10,000)(0.96)(170 - 80) = & 864,000 \text{ Btu} \\ \text{Bottoms} & (8333)(1.0)(210 - 80) = & 1,084,000 \text{ Btu} & \text{Bottoms} & (8333)(1.0)(T - 80) = & (8333T - 666,000) \text{ Btu} \\ & 1,084,000 = 8333T - 666,000 + 864,000 & & & & \\ & 886,000 = 8333T & & & & \\ & T = 106.5^\circ\text{F} & \leftarrow & \text{--- (b) ---} & & \end{array}$$

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31.8

(a) Compute heat of reaction for $C_7H_{16}(l) \rightarrow C_7H_8(l) + 4 H_2(g)$

$$\Delta \hat{H}_f^\circ (\text{kJ/g mol}): \quad -224.4 \quad +12.00 \quad 0$$

$$\text{mol. wt.:} \quad 100 \quad 92 \quad 2.016$$

$$\Delta \hat{H}_{Rxn}^\circ = 12.00 - (-224.4) = 236.4 \text{ kJ/g mol heptane}$$

Basis: 100 kg n-C₇H₁₆Material balance:

	kg	kg mol
In: n-C ₇ H ₁₆	100	1.00

$$\text{Out: toluene } (1.00) (0.15) (92) = 13.8 \quad 0.15$$

$$H_2 \quad (1.00) (0.15) (4) (2.02) = 1.21 \quad 0.60$$

$$n\text{-C}_7\text{H}_{16} (100) (0.85) = \underline{85.0} \quad 0.85$$

$$100.0$$

Energy Balance on reactor: $\Delta H_{\text{prod}} - \Delta H_{\text{react}} + \Delta H_{Rxn} = Q$

kJ

$$\Delta H_{\text{In}}: n\text{-C}_7\text{H}_{16} \text{ vapor} \quad 100 (1.88) (425 - 98.6) \quad 61,360$$

Solutions Chapter 31

$$\Delta H_{\text{vap}} \text{ at } 98.6^\circ\text{C} \quad (100) (318) \quad 31,800$$

$$n\text{-C}_7\text{H}_{16} \text{ liquid} \quad 100 (2.13) (98.6 - 25) \quad \underline{15,680}$$

$$\underline{108,840}$$

$$\Delta H_{\text{Out}}: \quad n\text{-C}_7\text{H}_{16} \text{ vapor} \quad 85.0 (1.88) (425 - 98.6) \quad 52,160$$

$$\Delta H_{\text{vap}} \text{ at } 98.6^\circ\text{C} \quad 85.0 (318) \quad 27,030$$

$$n\text{-C}_7\text{H}_{16} \text{ liquid} \quad 85.0 (2.13) (98.6 - 25) \quad 13,330$$

$$\text{Toluene vapor} \quad 13.8 (2.30) (425 - 110.8) \quad 9,970$$

$$\Delta H_{\text{vap}} \text{ } 110.8^\circ\text{C} \quad 13.8 (364) \quad 5,020$$

$$\text{Toluene liquid} \quad 13.8 (2.22) (110.8 - 25) \quad 2,630$$

$$H_2(g) \quad 0.60 [29.2 (425 - 0) - (28.7) (25.0)] \quad \underline{7,410}$$

$$\underline{117,550}$$

$$\Delta H_{Rxn} = (1000) (236.4) (0.15) = 35,460 \text{ kJ}$$

$$Q = 117,550 - 108,840 + 35,460 = 44,170 \text{ kJ/100 kg n-heptane fed}$$

(b) Energy Balance on extractor (ref. 25°C)

kJ

$$\text{In:} \quad n\text{-C}_7\text{H}_{16} \quad 85 (2.13) (18 - 25) \quad -1,267$$

$$\text{toluene} \quad 13.8 (2.22) (18 - 25) \quad -215$$

$$\text{solvent} \quad 138 (1.67) (38 - 25) \quad \underline{2,996}$$

$$\underline{1,514}$$

(continued)

Solutions Chapter 31

<u>Out:</u>	n-C ₇ H ₁₆	85 (2.13) (T - 25)	
	toluene	13.8 (2.22) (T - 25)	442.15 (T - 25)
	solvent	138 (1.67) (T - 25)	

Heat of Solution: (-23 kJ/kg) (13.8) -317

$$\Delta H_{\text{prod}} - \Delta H_{\text{react}} + \Delta H_{\text{soln}} = 0$$

$$442.15 (T - 25) - 1,514 + (-317) = 0$$

$$T = 29.14^{\circ}\text{C}$$

(c) Energy Balance on heat exchanger: (ref. 29.14°C)

(Assume fresh solvent is negligible in quantity.)

			<u>kJ</u>
<u>In:</u>	toluene	13.8 (2.22) (29.14 - 29.14)	0
	solvent	138 (1.67) (29.14 - 29.14)	0
	solvent	138 (1.67) (120 - 29.14)	<u>20,940</u>
			20,940
<u>Out:</u>	toluene	13.8 (2.22) (T - 29.14)	
	solvent	138 (1.67) (T - 29.14)	= 261 (T - 29.14)
	solvent	138 (1.67) (38 - 29.14)	2,040
			2,040 + 261 (T - 29.14)
			20,940 = 2040 + 261 (T - 29.14)
			T = 102°C

Solutions Chapter 31

(d) Energy Balance on still: (ref. 111°C, i.e., where ΔH_{vap} for toluene is given)

Assume the toluene vapor leaves at 120°C.

			<u>kJ</u>
<u>In:</u>	Solvent	138 (1.67) (100 - 111)	-2,535
	toluene	13.8 (2.22) (100 - 111)	- <u>337</u>
			<u>-2,872</u>
<u>Out:</u>	solvent	138 (1.67) (120 - 111)	2074
	toluene	13.8 (2.30) (120 - 111)	<u>286</u>
			<u>2360</u>

ΔH_{vap} of toluene assuming all entering the still vaporizes:

$$13.8 (364) \quad 5023$$

$$\begin{aligned} Q &= \Delta H = \Delta H_{\text{out}} - \Delta H_{\text{in}} + \Delta H_{\text{vap}} \\ &= 2360 - (-2872) + 5023 = 10,260 \text{ kJ/100 kg} \\ &= 103 \text{ kJ/kg n-heptane} \end{aligned}$$

31.9

Base temp. = 70°F

a. Material Balance:

$$\text{Benzene:} \quad (100,000) (0.50) = 50,000 \text{ lb}$$

$$\text{Toluene:} \quad (100,000) (0.40) = 40,000 \text{ lb}$$

$$\text{o-Xylene:} \quad (100,000) (0.10) = 10,000 \text{ lb}$$

(continued)

Solutions Chapter 31

Tower 1: overhead = $50,000/0.96 = 52,100$ lb Bz + toluene

Residue: 47,900 lb

Tower 2 residue = $10,000/0.99 = 10,100$ lb o-xyl + tol.

overhead = $47,900 - 10,100 = 37,800$ lb toluene

Calculation of T_1

heat exchanger:

$(175 - 70)(0.45)(52,100) = 2,460,000$ Btu above 70°F

$(75 - 70)(0.45)(52,100) = 117,000$ Btu in exit ΔH from tower 1

heat lost = $2,460,000 - 117,000 = 2,343,000$ Btu

temp. rise = $2,343,000/(0.46)(100,000) = 50.6^\circ\text{F}$

$T_1 = 70 + 50.6 = 120.6^\circ\text{F}$

b₁. Tower 1:

ΔH content of stream: $(100,000)(0.46)(185 - 70) = 4,830,000$

ΔH of reflux: $(6)(2,460,000) = \underline{14,740,000}$

ΔH in (Btu) 19,570,000

ΔH of residue: $(220 - 70)(0.48)(47,900) = 3,450,000$

ΔH of liquid: $(175 - 70)(7)(52,100)(0.45) = 17,240,000$

ΔH of vaporization: $(93.2)(1.8)(7)(52,100) = 61,400,000$

ΔH of vapor: $(0.285)(179 - 175)(7)(52,100) = \underline{417,000}$

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ΔH out (Btu): 82,507,000

ΔH supplied by reboiler in tower 1:

$82,507,000 - 19,570,000 = 62,937,000$ Btu

b₂. Tower 2

In: charge 3,450,000

Reflux: $(6)(37,800)(0.30)(230 - 70) = \underline{10,880,000}$

ht. in: (Btu) 14,330,000

Water used = $212,000 + 352,000 + 33,200 + 3550$

= 600,750 gal/day

d. Heat Balance on Tower 1:

charge: 4,830,000 cond: 61,857,000

steam: 62,937,000 Bz + tol: 2,460,000

residue: 3,450,000

total (Btu): 67,767,000 = 67,767,000

31.10

An important question to consider before attempting to solve the material and energy balances in a process is the feasibility of the flow sheet. The specified variables and data must contain enough information to solve the mass and energy balances written for the components of the flow sheet, and in particular must not overspecify or underspecify the problem as whole or for any component by providing more or fewer known state variables than there are design equations. If the flow sheet contains recycle streams, verification of the necessary data can become quite involved.

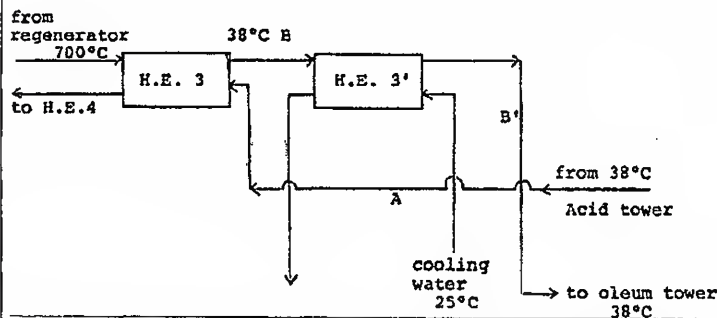
(continued)

The feasibility of the flow sheet itself is not determined solely by the given data and the energy and material balances of the system. One must examine the flow sheet to make sure that a solution is technically feasible, i.e., will the flow sheet produce the desired results or has something been overlooked (ignoring the fact that there are always problems in producing the desired results when actually building a process and trying to get it started.) Spotting mistakes is only partly an analytical process; it often requires familiarity with the units that make up the process and the materials that are being processed.

In the problem presented one major mistake is readily identified by examination of the flow sheet. Heat exchanger number three is overspecified. The incoming cold stream A and the exiting hot stream B cannot both be at the same temperature.

Another heat exchanger, using water as a coolant for B, is necessary.

31.11



A more critical view of the process must examine what the water vapor in the gas does in the SO_3 adsorption process. SO_3 and water form a sulfuric acid mist that is almost impossible to absorb and is highly corrosive. 97% H_2SO_4 is used as an absorbant in the acid tower precisely because it has an extremely low partial pressure of water vapor. Any acid mist formed would circulate through the process, not be absorbed, and corrode the equipment, eventually escaping with the cleaned stack gases, a more harmful pollutant than SO_2 alone. Thus one should be sure that no water can contact the SO_3 .

Barring leaks, the only source of water to the process is the incoming stack gas which undoubtedly contains water vapor from the combustion process:

Basis: 100 kg coal kg mol H_2

$$(5.2 \text{ kg H}) \left(\frac{\text{kg mol H}_2}{2 \text{ kg H}} \right) = 2.6 \text{ kg mol H}_2$$

2.6 kg mol H_2 is equivalent to

$$2.6 \text{ kg mol H}_2 \left(\frac{18 \text{ kg}}{\text{kg mol}} \right) = 47 \text{ kg H}_2\text{O}/100 \text{ kg coal}$$

To check whether or not water vapor will be present in the stack gas, the weight fraction of the water vapor in the combustion gases can be assumed to be equivalent to the weight fraction of water vapor in saturated air at a given temperature, assuming the stack gas approximates air in composition. The total amount of stack gas per 100 kg of coal is:

Basis: 100 kg coal

$$76.6 \text{ kg C} \left(\frac{\text{kg mol}}{12 \text{ kg}} \right) = 6.4 \text{ kg mol C}$$

$$5.2 \text{ kg H} \left(\frac{\text{kg mol H}_2}{2 \text{ kg H}_2} \right) = 2.6 \text{ kg mol H}_2$$

$$6.2 \text{ kg O} \left(\frac{\text{kg mol O}_2}{32 \text{ kg O}_2} \right) = 0.19 \text{ kg mol O}_2$$

$$2.3 \text{ kg S} \left(\frac{\text{kg mol}}{32 \text{ kg}} \right) = 0.072 \text{ kg mol S}$$

N and ash do not burn so that there is 90 kg of combusted material/100 kg coal.

(continued)

Air required:	<u>kg mol</u>
C + O ₂ + CO ₂	6.4 C
H ₂ + 1/2 O ₂ + H ₂ O	1/2(2.6) H ₂
S + O ₂ + SO ₂	<u>0.072 S</u>
	8.42
	- 0.19 O ₂ in coal
	8.23 mol O ₂ required from air

$$\frac{8.23 \text{ kg mol O}_2}{0.21 \text{ kg mol O}_2} \left| \frac{1 \text{ kg mol air}}{1 \text{ kg mol air}} \right| \frac{29 \text{ kg air}}{1 \text{ kg mol air}} (1.18)$$

$$= 1340 \text{ kg dry air}$$

$$\text{total weight of combustion gases} = 90 + 1340 = 1430 \text{ kg}$$

$$\text{weight fraction of water vapor} = \frac{47 \text{ kg}}{1430 \text{ kg}} = 0.033$$

Thus, the weight fraction of the water vapor is approximately 0.033, even assuming the air used for combustion is completely dry. Saturated air, even at 60°C, has a partial water pressure of 149.4 mm Hg. Then the weight fraction of water, assuming ideal gases is

$$\frac{p_{\text{H}_2\text{O}}}{p_{\text{air}}} = \frac{149.4 \text{ kg mol H}_2\text{O}}{(760 - 149.4) \text{ kg mol dry air}} \left| \frac{1 \text{ kg mol dry air}}{29 \text{ kg dry air}} \right|$$

$$\left| \frac{18 \text{ kg H}_2\text{O}}{1 \text{ kg mol H}_2\text{O}} \right| = \frac{0.15 \text{ kg H}_2\text{O}}{\text{kg air}}$$

Looking at the sorbent, the sorbent-air and stack gas streams will mix. Some water vapor will enter the Regenerator. If only 0.1% of the water vapor reaches the Regenerator

$$\frac{2.6 \text{ kg mol}}{100 \text{ kg coal}} \left| \frac{1 \text{ kg mol H}_2\text{O}}{1000 \text{ kg mol}} \right| \left| \frac{18 \text{ kg H}_2\text{O}}{1 \text{ kg mol H}_2\text{O}} \right| = \frac{4.7 \times 10^{-2} \text{ kg}}{100 \text{ kg coal}}$$

$$\frac{4.7 \times 10^{-2} \text{ kg H}_2\text{O}}{100 \text{ kg coal}} \left| \frac{2000 \text{ kg}}{1 \text{ metric ton}} \right| \left| \frac{340 \text{ metric ton coal}}{\text{hr}} \right|$$

$$= 320 \text{ kg H}_2\text{O/hr}$$

H₂O + SO₃ → H₂SO₄, so that the equivalent sulfuric acid is

$$\frac{320 \text{ kg H}_2\text{O}}{18 \text{ kg / kg mol H}_2\text{O}} \left| \frac{1 \text{ kg mol H}_2\text{SO}_4}{1 \text{ kg mol H}_2\text{O}} \right| \left| \frac{98 \text{ kg H}_2\text{SO}_4}{1 \text{ kg mol H}_2\text{SO}_4} \right| = 1740 \frac{\text{kg H}_2\text{SO}_4}{\text{hr}}$$

Thus, the flow sheet is not feasible unless the water vapor can be eliminated from entering the absorber.

31.12

a.	(NH ₄) ₂ SO ₄	(22)(500)	=	11,000
	Benzol	(15)(500)	=	7,500
	Toluol	(5)(500)	=	2,500
	Pyridine	(3)(500)	=	1,500
	Phenol	(5)(500)	=	2,500
	Naphthalene	(7)(500)	=	3,500
	Cresols	(20)(500)	=	10,000
	Pitch	(40)(500)	=	20,000
	Coke	(1500)(500)	=	750,000
	Gas	5,000,000 cu ft	=	199,670

$$\frac{34}{132} \times 11,000 = 2830 \text{ lb NH}_3 \text{ removed as (NH}_4\text{)}_2\text{SO}_4$$

$$\text{NH}_3 = \frac{36}{132} \times 22 \times 500 = 3000 \text{ lb}$$

b. Basis: 80°C = 178°F

(continued)

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<u>Primary tower</u>		
<u>Heat in</u>		$\times 10^{-6}$
Pitch	$20,000(.65)(5.25)$	$= 6.83$
Cresols	$10,000(.55)(219)+181+ (.50)(306)$	$= 4.54$
Toluene	$2,500(.53)(54)+155.9+ (.35)(471)$	$= 0.87$
Benzene	$7,500(.30)(525)$	$= 1.18$
Phenol	$2,500(.56)(183)+162+ (.45)(342)$	$= 1.05$
Pyridine	$1,500(.41)(61.2)+193.5+ (.28)(463.8)$	$= 0.52$
Naphthalene	$3,500(0.282)(0.4)+64.05+ (.40)(247.7)$ $+ 136 + (.35)(277)$	$= \underline{1.39}$ 16.38 Btu
<u>Heat Out</u>		
Pitch	$20,000(.65)(475)$	$= 6.18$
Cresols	$10,000(.55)(219)+181+ (.50)(104.2)$	$= 3.54$
Toluene	$2,500(.53)(54)+155.9+ (.35)(70.1)$	$= 0.52$
Benzene	$7,500(.30)(124.1)$	$= 0.28$
Phenol	$2,500(.56)(183.6)+162+ (.45)(41.4)$	$= 0.71$
Pyridine	$1,500(.41)(61.1)+193.2+ (.28)(163.9)$	$= 0.40$
Naphthalene	$3,500(.282)(0.36)+64.05+ (.40)(225)$	$= \underline{0.54}$ 12.17 Btu
$(16.38-12.17) \times 10^6 = 4.21 \times 10^6 \text{ Btu lost in primary tower}$		
<u>Secondary tower</u>		
<u>Out</u>		$\times 10^{-6}$
Benzene	0	$= 0.00$
Toluene	$2,500(.53)(54)+155.1+ (.35)(21.6)$	$= \underline{0.48}$ 0.48 Btu
<u>In</u>		$\times 10^{-6}$

Solutions Chapter 31

Benzene	0.28	
Toluene	<u>0.52</u>	$\therefore \text{Loss} = (0.80-0.48) \times 10^{-6}$
	0.80 Btu	$= 0.32 \times 10^{-6} \text{ Btu}$
c.	2500 lb Phenol	
	<u>2500</u> = 26.6 lb mol	
	94	
	26.6 lb mol NaOH (100% solution)	
	$\frac{26.6 \times 40}{H} = 2660 \text{ lb } 40\% \text{ NaOH required}$	
d	$\text{C}_5\text{H}_5\text{N}$ (MW = 79)	
	$\frac{(1500)(98)}{(79)(.5)} = 3720 \text{ lb } 50\% \text{ H}_2\text{SO}_4$	
e	Pyridine: $\text{H}_2\text{SO}_4 + 2 \text{ NaOH} + \text{Na}_2\text{SO}_4 + 2 \text{ H}_2\text{O} + \text{Pyridine}$	
	$\left(\frac{1860}{98}\right)(142) = 2700 \text{ lb Na}_2\text{SO}_4$	
	Phenol = $(13.3)(142) = 1890 \text{ lb}$	
	Total $\text{Na}_2\text{SO}_4 = 4590 \text{ lb}$	
f.	$(10,000)(500) = 5,000,000 \text{ cu ft}$	
	$(500)(2000)(300) = 300,000,000 \text{ Btu}$	
	$\frac{300,000,000}{555} = 540,000 \text{ cu ft}$	

(continued)

Solutions Chapter 31

$$\% \text{ gas needed} = \frac{541,000}{500,000,000} = 10.8\%$$

31.13

COM1 (GCOMP) INLET = FEED OUTLET = S001
 OUTLET PRESSURE, PSIA = 100.00 OUTLET TEMP, DEG F = 282.22
 ISENTROPIC TEMP, DEG F = 324.40 ISENTROPIC HORSEPOWER = 276.2
 INDICATED HORSEPOWER = 223.6 BRAKE HORSEPOWER = 279.5
 DISPLACEMENT, CFH = 98957.1 VOLUMETRIC EFFICIENCY = .8912

HEAT -HEATR -INLET = S001, OUTLET = S002
 OUTLET TEMP = 100.00 DEG F, PRESSURE DROP = 2.00 PSI
 DUTY = -.5683E+06 BTU/HR

COM2 (GCOMP) INLET = S002 OUTLET = OUT
 OUTLET PRESSURE, PSIA = 569.00 OUTLET TEMP, DEG F = 382.02
 ISENTROPIC TEMP, DEG F = 453.14 ISENTROPIC HORSEPOWER = 441.0
 INDICATED HORSEPOWER = 351.3 BRAKE HORSEPOWER = 439.1
 DISPLACEMENT, CFH = 33777.4 VOLUMETRIC EFFICIENCY = .8013

STREAM NAME:	FEED LBMOL/HR	OUT LBMOL/HR	S001 LBMOL/HR	S002 LBMOL/HR
1 HYDROGEN	418.000	418.000	418.000	418.000
2 METHANE	22.0000	22.0000	22.0000	22.0000
TOTAL LBMOL/HR	440.000	440.000	440.000	440.000
TOTAL LB/HR	1195.61	1195.61	1195.61	1195.61
1000 BTU/HR	301.37	1195.92	870.34	302.06
DEGREES F	100.00	382.02	282.22	100.00
PSIA	30.000	569.000	100.000	98.000
DENSITY, LB/FT3	.0136	.1684	.0340	.0442
MOLE FRAC VAPOR	1.0000	1.0000	1.0000	1.0000

Solutions Chapter 31

31.14

50% Recycle

STREAM NAME:	BOTM LBMOL/HR	FEED LBMOL/HR	OVHD LBMOL/HR	PROD LBMOL/HR	RECY LBMOL/HR
1 METHANE	.03163	3.11682	3.10100	.01582	.01581
2 ETHANE	.21331	3.32579	3.21911	.10666	.10663
3 PROPANE	3.51170	15.8752	14.1188	1.75585	1.75531
4 N-BUTANE	10.8815	15.0000	9.55772	5.44074	5.43919
5 ISO-BUTENE	13.1508	21.0000	14.4230	6.57538	6.57376
6 1,3-BUTADIENE	63.4611	95.0000	63.2610	31.7305	31.7a21
TOTAL LBMOL/HR	91.2500	153.318	107.681	45.6250	45.6128
TOTAL LB/HR	4964.56	8038.45	5555.51	2482.28	2481.62
1000 BTU/HR	-794.83	509.26	64.43	-397.42	-397.31
DEGREES F	41.00	185.00	41.00	41.00	41.00
PSIA	25.000	100.000	25.000	25.000	100.000
DENSITY, LB/FT3	38.9928	.8313	.2504	38.9928	38.9929
MOLE FRAC VAPOR	0.0000	1.0000	1.0000	0.0000	0.0000

STREAM NAME:	S001 LBMOL/HR	S002 LBMOL/HR	S003 LBMOL/HR
1 METHANE	3.13263	.01582	.01582
2 ETHANE	3.43242	.10666	.10666
3 PROPANE	17.6305	1.75585	1.75585
4 N-BUTANE	20.4392	5.44074	5.44074
5 ISO-BUTENE	27.5738	6.57538	6.57538
6 1,3-BUTADIENE	126.722	31.7305	31.7305
TOTAL LBMOL/HR	198.931	45.6250	45.6250
TOTAL LB/HR	10520.1	2482.28	2482.28
1000 BTU/HR	111.95	-397.42	-397.42
DEGREES F	126.20	41.00	41.00
PSIA	100.000	25.000	100.000
DENSITY, LB/FT3	0.0000	38.9928	38.9928
MOLE FRAC VAPOR	.8232	0.0000	0.0000

25% Recycle

(continued)

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STREAM NAME:	BOTM	FEED	OVHD	PROD	RECY
	LBMOL/HR	LBMOL/HR	LBMOL/HR	LBMOL/HR	LBMOL/HR
1 METHANE	.02109	3.11682	3.10100	.01582	.00527
2 ETHANE	.14225	3.32579	3.21911	.10668	.03556
3 PROPANE	2.34175	15.8752	14.1189	1.75631	.58543
4 N-BUTANE	7.25626	15.0000	9.55780	5.44219	1.81406
5 ISO-BUTENE	8.76940	21.0000	14.4229	6.57705	2.19235
6 1,3-BUTADIENE	42.3184	95.0000	63.2612	31.7388	10.5796
TOTAL LBMOL/HR	60.8492	153.318	107.681	45.6369	15.2123
TOTAL LB/HR	3310.57	8038.45	5555.52	2482.93	827.642
1000 BTU/HR	-530.03	509.26	64.43	-397.52	-132.51
DEGREES F	41.00	185.00	41.00	41.00	41.00
PSIA	100.000	25.000	100.000	25.000	25.000
DENSITY, LB/FT3	38.9928	.8313	.2504	38.9928	38.9928
MOLE FRAC VAPOR	0.0000	1.0000	1.0000	0.0000	0.0000

STREAM NAME:	S001	S002	S003
	LBMOL/HR	LBMOL/HR	LBMOL/HR
1 METHANE	3.12209	.00527	.00527
2 ETHANE	3.36136	.03556	.03556
3 PROPANE	16.4606	.58544	.58544
4 N-BUTANE	16.8141	1.81406	1.81406
5 ISO-BUTENE	23.1924	2.19235	2.19235
6 1,3-BUTADIENE	105.580	10.5796	10.5796
TOTAL LBMOL/HR	168.530	15.2123	15.2123
TOTAL LB/HR	8866.09	827.643	827.643
1000 BTU/HR	376.75	-132.51	-132.51
DEGREES F	137.17	41.00	41.00
PSIA	100.000	25.000	100.000
DENSITY, LB/FT3	.9260	38.9928	38.9928
MOLE FBAC VAPOR	1.0000	0.0000	0.0000

No Recycle

STREAM RECY IS ZERO
 STREAM S002 IS ZERO
 STREAM S003 IS ZERO

Solutions Chapter 31

STREAM NAME:	BOTM	FEED	OVHD	PROD	RECY
	LBMOL/HR	LBMOL/HR	LBMOL/HR	LBMOL/HR	LBMOL/HR
1 METHANE	.01582	3.11682	3.10100	.01582	3.11682
2 ETHANE	.10668	3.32579	3.21911	.10668	3.32579
3 PROPANE	1.75631	15.8752	14.1189	1.75631	15.8752
4 N-BUTANE	5.44219	15.0000	9.55781	5.44219	15.0000
5 ISO-BUTENE	6.57705	21.0000	14.4229	6.57705	21.0000
6 1,3-BUTADIENE	31.7388	95.0000	63.2612	31.7388	95.0000
TOTAL LBMOL/HR	45.6369	153.318	107.681	45.6364	153.318
TOTAL LB/HR	2482.93	8038.45	5555.52	2482.93	8038.45
1000 BTU/HR	-397.52	509.26	64.43	-397.52	509.26
DEGREES F	41.00	185.00	41.00	41.00	185.00
PSIA	25.000	100.000	25.000	25.000	100.000
DENSITY, LB/FT3	38.9928	.8313	.2504	38.9928	.8313
MOLE FRAC VAPOR	0.0000	1.0000	1.0000	0.0000	1.0000

31.14

STREAM COMPONENT FLOW RATES - KG MOLS/HR

STREAM ID	1	2	3	4	5	6
NAME	INLET GAS					
PHASE	MIXED	VAPOR	VAPOR	VAPOR	LIQUID	MIXED
1 NITROGEN	181.0000	179.6106	179.6156	179.7343	0.0087	179.7345
2 CO2	1930.0000	1827.1284	1827.1284	1832.9626	0.5438	1832.9626
3 METHANE	14515.0000	14117.3906	14117.3906	14143.7344	2.3537	14143.7344
4 ETHANE	9072.0000	8010.3682	8010.3682	8064.8525	5.2165	8064.8525
5 PROPANE	7668.0000	5138.6318	5138.6318	5228.9082	10.6500	5228.9082
6 BUTANE	770.0000	399.4697	399.4697	413.3093	1.7963	413.3092
7 BUTANE	3810.0000	1229.4946	1229.4946	1285.9678	7.6706	1285.9675
8 PENTANE	953.0000	239.5409	239.5409	262.0803	3.3762	262.0803
9 PENTANE	1633.0000	339.8380	339.8380	579.3123	6.1499	579.3123
10 HEXANE	1542.0000	129.1421	129.1421	165.9431	7.0540	165.9431
11 BP135	1973.0000	93.9453	93.9453	154.5959	65.6602	154.5959
12 BP260	9072.0000	0.2617	0.2617	0.0036	0.2616	0.0036
13 BP500	9072.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TOTALS	70775.0000	31704.8047	31704.8047	32111.3828	111.5435	32111.3828
TEMPERATURE, DEG C	45.0000	45.0051	60.0000	55.7191	60.0000	60.0000
PRESSURE, KPA	450.0000	450.0000	1100.0000	1100.0000	1100.0000	2600.0000
H. MM KG/HR	462.6024	370.9030	349.0496	351.7608	0.6275	332.5598
MOLE FRACT LIQUID	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000
RECYCLE CONVERGENCE	0.0000	0.0000	0.0000	0.0000	-0.0060	0.0000

STREAM ID	7	8	9	10	11	12
NAME				COMPR VAPOR		CONDENSATE
PHASE	VAPOR	LIQUID	MIXED	VAPOR	LIQUID	LIQUID
1 NITROGEN	180.7536	0.1279	180.7536	179.6042	1.1493	1.3931
2 CO2	1858.4001	6.3981	1858.4001	1826.5083	31.8919	93.4211
3 METHANE	14283.7637	28.7751	14283.7637	14114.6504	169.1123	399.9786
4 ETHANE	8223.9930	60.4659	8223.9930	8004.0049	219.0054	1067.4871
5 PROPANE	5386.3184	101.4302	5386.3174	5127.0469	259.2706	2132.2896
6 BUTANE	428.6809	15.6834	428.6808	397.5724	31.1084	272.3384
7 BUTANE	1335.0337	64.3417	1335.0334	1221.4304	115.6030	1588.2264
8 PENTANE	270.5154	26.0022	270.5154	236.0146	34.5007	716.8571
9 PENTANE	368.9042	45.7813	368.9041	333.4230	55.4790	1299.3508
10 HEXANE	157.5544	44.0534	157.5544	121.7904	35.7641	1419.9502
11 BP135	58.9876	126.3875	58.9876	28.2376	30.7300	11947.1621

(continued)

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12 BP2M	0.0000	0.0036	0.0000	0.0000	0.0000	9071.9930
13 BP500	0.0000	0.0000	0.0000	0.0000	0.0000	9072.0000
TOTALS	32572.8906	519.4429	32572.8906	31590.2891	982.6025	9182.4453
TEMPERATURE, DEG C	57.0695	57.0695	60.0000	60.0000	60.0000	45.0051
PRESSURE, KPA	2600.0000	2600.0000	6200.0000	6200.0000	6200.0000	450.0000
H. MM KJ/HR	335.5528	3.3357	270.3684	364.0405	6.3286	132.4387
MOLE FRACT LIQUID	0.0000	1.0000	0.0302	0.0000	1.0000	0.0000
RECYCLE CONVERGENCE	0.0000	0.0045	0.0000	0.0000	0.0028	0.0000

Heat duty:

Exchanger No.	Q (MM kJ/hr)	Temp. (°C)	Press. (kPa)
1	82.04	60	1100
2	120.33	60	2600
3	165.35	60	6200

31.15

STEAM ID	1	2	3	4	5	6
NAME INLET GAS						
PHASE VAPOR	MIXED	MIXED	VAPOR	LIQUID	MIXED	
1 NITROGEN	211.9104	211.9104	211.9104	198.0745	15.8359	13.8359
2 METHANE	1957.0227	1957.0227	1510.2052	446.7177	1957.0227	446.7177
3 ETHANE	205.7486	205.7486	205.7486	55.7909	149.9577	149.9577
4 PROPANE	152.4361	152.4361	152.4361	10.4024	141.8337	141.8337
5 BUTANE	26.5223	26.5223	26.5223	0.6496	25.8727	25.8727
6 BUTANE	65.3680	65.3680	65.3680	0.9780	64.3892	64.3892
7 PENTANE	18.4852	18.4852	18.4852	0.0892	18.3960	18.3960
8 PENTANE	21.9679	21.9679	21.9679	0.0724	21.8956	21.8956
9 HEXANE	11.2519	11.2519	11.2519	0.0000	11.2433	11.2433
10 HEPTANE	8.3050	11.3050	11.3050	0.0014	8.3026	11.3036
TOTALS	2679.0156	2679.0156	1776.5720	902.4447	2679.0156	902.4445
TEMPERATURE, DEG F	120.0000	7.4668	84.0000	-84.0000	-134.7104	
PRESSURE, PSIG	588.0000	578.0000	573.0000	573.0000	573.0000	125.0000
H. MM BTU/HR	4.9855	-0.2978	-5.3106	-2.4487	-2.8619	-2.8619
MOLE FRACT LIQUID	0.0000	0.1135	0.3369	0.0000	1.0000	0.6545
RECYCLE CONVERGENCE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STREAM COMPONENT FLOW RATES - LD MOLS/HR						
STREAM ID	7	8	9	10	11	3%
NAME		LIQUIDS	RESIDUE			
PHASE MIXED	VAPOR	LIQUID	VAPOR	VAPOR	MIXED	
1 NITROGEN	198.0745	211.9109	0.0000	211.9109	211.9109	211.9104
2 METHANE	1510.3052	1952.8789	4.1493	1952.8789	1952.8789	1957.0227
3 ETHANE	55.7909	30.4285	175.3177	30.4285	30.4285	205.7486
4 PROPANE	10.4024	0.4553	151.9786	0.4553	0.4553	152.4361
5 BUTANE	0.6496	0.0040	26.5179	0.0040	0.0040	26.5221
6 BUTANE	0.9788	0.0025	65.3645	0.0025	0.0025	65.3600
7 PENTANE	0.0892	0.0000	18.4849	0.0000	0.0000	18.4852
8 PENTANE	0.0724	0.0000	21.9676	0.0000	0.0000	21.9679
9 HEXANE	0.0086	0.0000	11.2517	0.0000	0.0000	11.2519
10 HEPTANE	0.0014	0.0000	8.3048	0.0000	0.0000	8.3050
TOTALS	1776.5720	2195.6792	483.3371	2195.6792	2195.6792	2679.0156

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TEMPERATURE, DEG F	-174.6392	-170.2356	24.8966	118.0000	156.7519	-84.0000
PRESSURE, PSIG	125.0000	125.0000	125.0000	120.0000	160.4095	573.0000
IL MM BTU/HR	-3.4297	-3.7743	-0.1439	1.5090	2.3917	-53.105
MOLE FRACT LIQUID	0.0622	0.0000	1.0000	0.0000	0.0000	0.3369
RECYCLE CONVERGENCE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

SUMMARY OF HEAT EXCHANGE UNITS

5 UNIT E1, GAS-GAS EX, IS A HEAT EXCHANGER

OPERATING CONDITIONS

DUTY, MM KJ/HR	5.57417
WEIGHTED LMTD, DEG K	30.087
F FACTOR	1.00000
MTD, DEG K	30.087
U * A, KJ/HR DEG K	185265.594

HOT SIDE CONDITIONS	INLET	OUTLET
FEED(S)	1	2
MIXED PRODUCT		
VAPOR, KG MOLS/HR	1215.1807	1077.3076
M KGS/HR	27.3531	21.1992
CP, KJ/KG - DEG K	2.2837	2.3829
LIQUID, KG MOLS/HR	0.0000	137.8730
M KGS/HR	0.0000	6.1539
CP, KJ/KG - DEG K	0.0000	2.3937
TOTAL, KG MOLS/HR	1215.1807	1215.1807
CONDENS VAPORIZATION, KG MOLS/HR		137.8730
TEMPERATURE, DEG K	322.039	259.520
PRESSURE, KPA	4155.435	4086.487

COLD SIDE CONDITIONS	INLET	OUTLET
FEED(S)	8	
VAPOR PRODUCT		10
VAPOR, KG MOLS/HR	995.9431	995.9431
M KGS/HR	17.3280	17.3280
CP, KJ/KG - DEG K	2.1518	2.1288
LIQUID, KG MOLS/HR	0.0000	0.0000
M KGS/HR	0.0000	0.0000

(continued)

Solutions Chapter 31

CP, KJ /KG - DEG K	0.0000	0.0000
TOTAL, KG MOLS/HR	995.9431	995.9431
CONDENS(VAPORIZ)ATION, KG MOLS/HR		0.0000
TEMPERATURE, DEG K	160.797	316.483
PRESSURE, KPA	963.168	928.694

HEAT EXCHANGER ZONE ANALYSIS

		DELTA T	AT COLD			
		INLET,	OUTLET, LMTD,	-----DUTY-----		
DUTY						TOTAL
ZONE	DEG K	DEG K	DEG K	MM KJ /HR	PERCENT	MM KJ /HR
1	98.72	80.44	89.27	1.073	19.26	1.073
2	80.44	61.43	70.51	1.073	19.26	2.147
3	61.43	42.58	51.43	1.073	19.26	3.220
4	42.58	24.59	32.77	1.073	19.26	4.293
5	24.59	7.86	14.67	1.073	19.26	5.367
6	7.86	5.56	6.64	0.208	3.72	5.574

32.1



The amount of solution decreases at a rate of $15 - 10 = 5$ kg/min. By an overall balance, the amount of solution after t min is

$$(100 - 5t) \text{ kg}$$

Let χ = kg of salt per kg of solution in the tank after t min

$$\chi(0) = 0.60$$

Then $d\chi/dt$ = rate of change of the concentration in the tank. Salt balance at any time t

$$\text{Accumulation} = \text{In} - \text{Out}$$

$$(100 - 5t) \frac{d\chi}{dt} = (10)(0.6) - 15\chi$$

Separating variables

$$\frac{d\chi}{1 - 15\chi} = \frac{dt}{100 - 5t}$$

Integrating from 0 to 10 min

$$\int_{0.6}^{\chi} \frac{d\chi}{1 - 15\chi} = \int_0^{10} \frac{dt}{100 - 5t}$$

$$\ln \frac{(1 - 15\chi)}{(1 - 9)} = 31 \ln \frac{(100 - 50)}{100}$$

Solving: $\chi = 2/15$

$$\text{kg of solution after 10 min} = 100 - 50 = 50 \text{ kg}$$

$$\text{kg of salt in the tank} = (2/15)(50) = \boxed{6.67 \text{ kg}}$$

32.2

Assume: (1) Ideal gas law applies

(2) Rate of inflow = rate of outflow

Propane balance: Accumulation = Input - Output

$$\left[\frac{x \text{ ft}^3 \text{ propane}}{\text{ft}^3 \text{ mixture}} \right]_{t+\Delta t} - \left[\frac{x \text{ ft}^3 \text{ propane}}{\text{ft}^3 \text{ mixture}} \right]_t (1500 \text{ ft}^3)$$

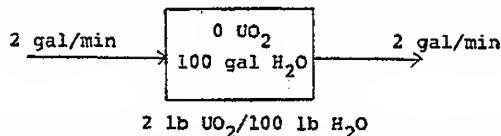
$$= \frac{0 \text{ ft}^3 \text{ propane}}{\text{ft}^3 \text{ mixture}} \Big|_{30 \text{ ft}^3/\text{min}} \Delta t \text{ min}$$

$$- \frac{x \text{ ft}^3 \text{ propane}}{\text{ft}^3 \text{ mixture}} \Big|_{30 \text{ ft}^3/\text{min}} \Delta t \text{ min}$$

$$1500 \int_1^{0.01} \frac{dx}{x} = -30 \int_0^1 dt \rightarrow 1500 \ln x \Big|_1^{0.01} = -30 t \Big|_0^1$$

$$\boxed{t = 230.5 \text{ min}}$$

32.3



Ignore volume changes as the slurry concentration changes, and assume UO_2 in the H_2O does not change the density of the solution from that of water. The independent variable is $t = \text{time}$; dependent variable is $x = \text{lb UO}_2 \text{ in tank} / \text{lb H}_2\text{O in tank}$.

At $t = 0$, $x = 0$

Material Balance on UO_2 in Δt :

$$\text{In} \quad \frac{2 \text{ gal} | 8.33 \text{ lb H}_2\text{O} |}{\text{min} | \text{ gal H}_2\text{O} |} \frac{2 \text{ lb UO}_2}{100 \text{ lb H}_2\text{O}} \bigg| \frac{\Delta t \text{ min}}{100 \text{ lb H}_2\text{O}}$$

$$\text{Out} \quad - \frac{2 \text{ gal} | 8.33 \text{ lb H}_2\text{O} |}{\text{min} | \text{ gal H}_2\text{O} |} \frac{x \text{ lb UO}_2}{\text{lb H}_2\text{O}} \bigg| \frac{\Delta t \text{ min}}{100 \text{ lb H}_2\text{O}} =$$

$$\text{Accumulation} \quad \frac{x \text{ lb UO}_2}{\text{lb H}_2\text{O}} \bigg| \frac{500 \text{ lb H}_2\text{O}}{100 \text{ lb H}_2\text{O}} \bigg|_{t+\Delta t} - \frac{x \text{ lb UO}_2}{\text{lb H}_2\text{O}} \bigg| \frac{500 \text{ lb H}_2\text{O}}{100 \text{ lb H}_2\text{O}} \bigg|_t$$

$$\frac{(2)(8.33)}{(500)} \int_0^{\infty} dt = \int_0^x \frac{dx}{0.02 - x} = [-\ln[(0.02) - x]]_0^x \quad \boxed{x = 0.0173 \text{ lb UO}_2 / \text{lb H}_2\text{O}}$$

32.4

Assume: (1) Ideal gas law applies

(2) Rate of inflow = rate of outflow

O_2 balance: Accumulation = Input - Output

$$\left[\frac{x \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \right]_{t+\Delta t} - \left[\frac{x \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \right]_t \left[\frac{94 \text{ m}^3 \text{ free vol}}{100 \text{ m}^3 \text{ reactor vol}} \right] \left[\frac{200 \text{ m}^3}{\text{min}} \right]$$

$$= \frac{0 \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \bigg| \frac{20 \text{ m}^3}{\text{min}} \bigg| \frac{\Delta t \text{ min}}{100 \text{ m}^3 \text{ reactor vol}} - \frac{x \text{ m}^3 \text{ O}_2}{\text{m}^3 \text{ mixture}} \bigg| \frac{20 \text{ m}^3}{\text{min}} \bigg| \frac{\Delta t \text{ min}}{100 \text{ m}^3 \text{ reactor vol}}$$

$$188 \int_{0.210}^{0.001} \frac{dx}{x} = -20 \int_0^t dt \rightarrow 188 \ln x \bigg|_{0.210}^{0.001} = -20 t \bigg|_0^t$$

$$\boxed{t = 50.3 \text{ min}}$$

32.5

$V_1 = \text{initial volume}$

$$= (4/3) (\pi)^3 = (4/3) (\pi) (10)^3 = 4190 (\text{ft})^3$$

$V_2 = \text{final volume}$

$$= (4/3) (\pi) (9.5)^3 = 3590 (\text{ft})^3$$

(a) At constant pressure:

(continued)

$$\frac{dV}{dt} = 5; \quad \int_{V_1}^{V_2} dV = 5 \int_0^t dt; \quad 5t = 4190 - 3590$$

$$t = 120 \text{ mi}$$

- (b) Assuming the rate of escaping is proportional to the volume and initially at $5(\text{ft})^3/\text{min}$.

$$\frac{dV}{dt} = KV; \quad 5 = KV_1 = 4190 K \text{ or } K = \frac{5}{4190}$$

$$\int_{V_1}^{V_2} \frac{dV}{V} = \frac{5}{4190} \int_0^t dt$$

$$t = \frac{4190}{5} \ln \left(\frac{V_2}{V_1} \right) = 858 \ln \frac{4190}{3590} = 131 \text{ min}$$

- (c) Not without another piece of information as the mass balance contains two unknowns, such as p and V .

32.6

Let the moisture content be w

$$\text{then, } \frac{dw}{dt} = kw$$

$$\int_{w_0}^{w_0/2} \frac{dw}{w} = k \int_0^{15} dt$$

$$\ln w \frac{w_0/2}{w_0} = kt^{15} \quad \text{so} \quad k = 0.046 \text{ and } \int_{w_0}^w \frac{dw}{w} = k \int_0^t dt$$

$$\ln \frac{w}{w_0} = kt$$

$$\text{At } t = 15, w = w_0/2; k = \frac{\ln w_0/2}{15} = -0.463$$

$$\ln \left(\frac{w}{w_0} \right) = -0.0463t$$

$$\text{When } w = 0.1 w_0, t = \frac{\ln \frac{0.1 w_0}{w_0}}{-0.0463} = 49.7 \text{ min}$$

32.7

- a. Ignore friction, non-ideality at the discharge and the orifice coefficient and use instead

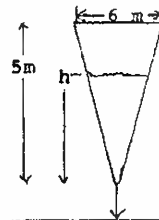
$$0.020 (2 + h^2) \text{ m}^3/\text{min}$$

$$\text{Vol cone} = 1/3 \pi r^2 h$$

$$\frac{r}{h} = \frac{3}{5}; r = \frac{3}{5} h \quad \therefore V = \frac{9}{75} \pi h^3$$

$$\frac{dV}{dt} = \frac{9}{25} \pi h^2 \frac{dh}{dt} = 1.13 h^2 \frac{dh}{dt} \frac{(\text{m})^3}{\text{min}}$$

$$= 0.020 (2 + h^2)$$



(continued)

$$\int_{h_1}^{h_2} \frac{56.6 h^2 dh}{2 + h^2} = - \int_0^t dt = -t$$

$$t = -56.5 [h]_{h_1}^{h_2} + \left[\frac{113}{\sqrt{2}} \tan^{-1} \sqrt{2}h \right]_{h_1}^{h_2}$$

$$h_1 = 5\text{m} \quad h_2 = (3\sqrt{0.25}) \quad h_1 = 3.15\text{ m}^3$$

$$\therefore t = -56.6 (3.15 - 5) + 79.9 (\tan^{-1} 4.45 - \tan^{-1} 7.07)$$

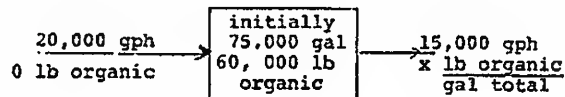
$$t = 98 \text{ min}$$

b. The rate of discharge at that time is:

$$\frac{dV}{dt} = 0.02 (2 + h^2)$$

$$= 0.02 (2 + (3.15)^2) = 0.24 \text{ m}^3 / \text{min}$$

32.8



(1) Overall Balance:

Let y = total gal of mixture in the tank at time t (in hours)

$$\text{then } \frac{dy}{dt} = 20,000 - 15,000 = 5000$$

$$\int_{75,000}^y dy = 5000 \int_0^t dt$$

$$y = 5000 (15 + t)$$

(2) Organic Material Balance:

Let $x = \frac{\text{lb organic}}{\text{gal of mix}}$ in the tank at time t .

$$\text{Initially, } x = 60,000/75,000 = 0.8$$

Total amount of organic in the tank at time t is (yx) lbs.

Then the rate of accumulation of organic will be $d(yx)/dt$, lb/hr.

Rate Accumulation = Rate in - Rate out

$$\frac{d(yx)}{dt} = 0 - 15,000 x$$

$$y \frac{dx}{dt} + x \frac{dy}{dt} = -15,000$$

$$\frac{dx}{dt} = \frac{-20,000x}{5000(15 + t)}$$

$$\int_{0.8}^x \frac{dx}{x} = - \int_0^3 \frac{4dt}{15 + t}; \quad \ln \frac{x}{0.8} = 4 \ln \frac{15}{18}$$

$$x = 0.396$$

The total wt of organic material in the tank after 3 hrs is:

$$yx = (75,000 + (5000)(3)) (0.396) = 34,700 \text{ lbs}$$

(continued)

Alternative Solution:

If x = total lb of organic in the tank at any time t , then the concentration of organic is x/y .

The balance becomes:

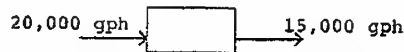
$$\frac{dx}{dt} = - \frac{15,000 \text{ gal } x \text{ lb}}{\text{hr } y \text{ gal}}$$

$$\int_{60,000}^x \frac{dx}{x} = - \int_0^3 \frac{15,000 \text{ dt}}{5000 (15 + t)}$$

$$\ln \frac{x}{60,000} = -3 \ln \frac{18}{15}$$

$$X = \boxed{34,700 \text{ lb organic}}$$

32.9



$$\text{Suspension Rate} = K(10-x) \text{ lb/hr}$$

- (1) Overall Balance: Assuming the sludge does not affect the volume of the mixture in the tank, the overall balance will be the same as that in Prob. 7.8, i.e. $y = 5000 (15+t)$ gal.

- (2) Organic Balance:

Let x = lb of organic in suspension per gal of total in the tank at time t in hours.
 z = lb of sludge going into suspension at time t .

Rate of sludge going into suspension:

$$\frac{dz}{dt} = K(10-x)$$

$$@ x = 0 \quad y = 75,000 \text{ gal}$$

$$\frac{dz}{dt} = \frac{0.05 \text{ lb}}{(\text{min})(\text{gal})} \left| \frac{75,000 \text{ gal}}{60 \text{ min}} \right| \frac{60 \text{ min}}{\text{hr}} = K(10) \text{ lb/gal}$$

$$\text{Thus } K = \frac{(0.05)(75,000)(60)}{10} = 22,500 \text{ gal/hr}$$

$$\text{Rate of accumulation of organic: } \frac{d(yx)}{dt}$$

$$\text{Rate Acc.} = \text{Rate in} - \text{Rate out}$$

$$\frac{d(yx)}{dt} = [22,500(10-x)] - 15,000x$$

$$= y \frac{dx}{dt} + x \frac{dy}{dt}$$

$$\frac{dx}{dt} = \frac{45 - 8.5x}{15 + t}$$

$$\int_{0.8}^x \frac{dx}{5.3-x} = \int_0^3 \frac{8.5 \text{ dt}}{15+t}; \quad -\ln \frac{5.3-x}{5.3-0.8} = 8.5 \ln \frac{18}{15}$$

$$\text{Solving, } x = 4.345 \text{ lb/gal}$$

The total weight of organic in the tank after 3 hrs is $(90,000) (4.345)$

$$= \boxed{391,050 \text{ lbs}}$$

Alternative Solution:

(continued)

Solutions Chapter 32

Let $x = \text{lb of organic in tank at time } t$

conc. = x/y , then

$$\frac{dx}{dt} = K(10 - x/y) - 15,000(x/y)$$

$$\frac{dx}{dt} + \frac{37,500x}{5000(15+t)} = 225,000$$

$$\frac{dx}{dt} + \frac{75x}{15+t} = 225,000; \quad \frac{d(15+t)^{7.5}x}{dt} = 225,000(15+t)^{7.5}$$

$$(15+t)^{7.5}x = \left(\frac{225,000}{8.5}\right)(15+t)^{8.5} + C$$

$$x = 26,500(15+t) + C(15+t)^{-7.5}$$

when $t = 0$, $x = 60,000$, and $C = -338,000 (15)^{7.5}$

when $t = 3$; $x = 27,500 (18) - 338,000 (15/18)^{7.5}$

32.10

Let C , x , y = the number of moles of C , x , and y respectively at time t .

(1) C balance: $C_0 = 1$, initial moles of C

$$\frac{dC}{dt} = -kC; \quad \int_{C_0}^C \frac{dC}{C} = -k \int_0^t dt$$

$$\ln \frac{C}{C_0} = -kt; \quad C = C_0 e^{-kt} = e^{-kt}$$

(2) x balance:

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$$\frac{dx}{dt} = kC = ke^{-kt}$$

$$\int_0^x dx = \int_0^t ke^{-kt} dt$$

$$x = 1 - e^{-kt}$$

$$e^{-kt} = 1 - e^{-kt} \quad \text{or} \quad 2e^{-kt} = 1$$

$$\ln 1/2 = -kt, \quad \text{or} \quad t = \frac{\ln 2}{k}$$

32.11

Mass balance:

Accumulation = Input - Output

$$d(\rho V) = 0 - [U_1 A_1 \rho dt + U_2 A_2 \rho dt]$$

$$\text{where } V = \pi(l^2)H \text{ m}^3, \quad A_1 = \pi(2.5)^2 \text{ cm}^2, \quad A_2 = \pi(5)^2 \text{ cm}^2$$

$$V = c\sqrt{2gh}, \quad c = 0.61, \quad g = 9.80 \text{ m/s}^2 \quad \begin{array}{l} h = \text{height of H}_2\text{O level from orifice} \\ H = \text{height of H}_2\text{O level from bottom} \\ h_1 = H-1 \text{ \& } h_2 = H-0.5 \end{array}$$

$$\text{Assume } \rho \text{ is constant} \quad \text{Then } dV = \frac{9\pi dH}{2} \\ = -0.61\sqrt{2 \times 9.80} (\pi \times 10^{-4}) [(6.25\sqrt{H-1} + 25\sqrt{H-0.5})] dt$$

$$-3.00 \times 10^{-5} \int_0^t dt = \int_{10}^5 \frac{dH}{6.25\sqrt{H-1} + 25\sqrt{H-0.5}}$$

(continued)

Solutions Chapter 32

$$-3.00 \times 10^{-5} t = \int_{10}^5 \frac{dH}{\sqrt{H-1} + 25\sqrt{H-0.5}} \times \frac{\sqrt{H-1} - 25\sqrt{H-0.5}}{\sqrt{H-1} - 25\sqrt{H-0.5}}$$

$$= \int_{10}^5 \left[\frac{\sqrt{H-1}}{((625/2)-1)} - \frac{25\sqrt{H-0.5}}{((625/2)-1) - 625H} \right] dH$$

Let $H-1 = x^2$ $H-0.5 = y^2$

$H = x^2 + 1$ $H = y^2 + 0.5$

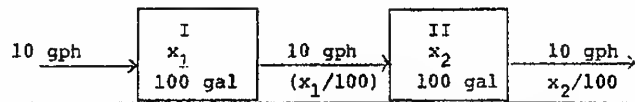
$dH = 2x dx$ $dH = 2y dy$

$$(-3.00) 10^{-5} t = \int \frac{x \cdot 2x \cdot dx}{\left(\frac{625}{2} - 1\right) - 625(x^2 + 1)}$$

$$-25 \int \frac{y \cdot 2y \cdot dy}{\left(\frac{625}{2} - 1\right) - 625(y^2 + 0.5)}$$

$$t = 2.02 \times 10^3$$

32.12



Let x_1, x_2 be the number of lb of A in tank I or II at any time t respectively

A. Balance in tank I.

Solutions Chapter 32

$$\frac{dx_1}{dt} = 0 - \left(\frac{10}{100}\right) x_1 = -0.1x_1$$

$$\int_{10}^{x_1} \frac{dx}{x} = -0.1 \int_0^t dt$$

$$x_1 = 10 e^{-0.1t}$$

for $t = 3$ hr; $x_1 = 10e^{-0.3} = 7.41$ lb

Conc. of A in tank A = $\boxed{0.0741 \text{ lb/gal}}$

A Balance in tank II

$$\frac{dx_2}{dt} = 10\left(\frac{x_1}{100}\right) - 10\left(\frac{x_2}{100}\right)$$

Since $x_1 = 10e^{-0.1t}$

$$\frac{dx_2}{dt} = e^{-0.1t} - 0.1x_2$$

$$\frac{dx_2}{dt} + 0.1x_2 = e^{-0.1t}$$

$(D + 0.1)x_2 = e^{-0.1t}$ where $D = d/dt$

Particular integral

$$P.I. = e^{-0.1t}/D + 0.1 = (e^{-0.1t})/(D - 0.1 + 0.1)$$

$$= te^{-0.1t}$$

The general solution is

$$x_2 = Ce^{-0.1t} + te^{-0.1t}$$

(continued)

when $t = 0$, $x_2 = 10$, and $C = 10$

$$x_2 = e^{-0.3} (10 + 3) = 9.64 \text{ lb}$$

Conc. of A in tank II = $[0.0964 \text{ lb / gal}]$

32.13

Assuming ρ to be constant, the material balance is as follows: Accumulation = inflow - outflow

$$\frac{dV}{dt} = Q_i - Q_o$$

$$= 2 - 0.01V$$

$$\left. \frac{dV}{dt} \right|_{t=0} = 1.5 \quad [V \text{ increases}]$$

$$\int_{50}^{100} \frac{dV}{2 - 0.01V} = \int_0^t dt$$

$$- \frac{1}{0.01} \ln(V - 200) \Big|_{50}^{100} = t \rightarrow t \ln\left(\frac{100}{500}\right) = -0.01t$$

$$t = -100 \ln\left(\frac{100}{500}\right) = [40.6 \text{ min}]$$

32.14

Let $x = \text{mg of fission product in the tank at any time } t$; when $t = 0$, $x = (10)(3.785)(10,000) = 3.785 \times 10^5 \text{ mg}$

Rate of change = Rate in - Rate out - Rate decay

$$\frac{dx}{dt} = (10)(3.785)(100) - 100\left(\frac{x}{10,000}\right) - 0.01x$$

$$= 3785 - 0.02x$$

$$\int_{3.785 \times 10^5}^x \frac{dx}{3785 - 0.02x} = \int_0^{24} dt = 24$$

$$-\frac{1}{0.02} \ln(3785 - 0.02x) \Big|_{3.785 \times 10^5}^x = 24$$

$$x = 306,000 \text{ mg}$$

conc. in the tank at the end of the first 24 hr =

$$30.6 \text{ mg/gal} \rightarrow [8.1 \text{ mg / liter}]$$

b. $\frac{dx}{dt} = -0.01x$

$$\int_{306,000}^x \frac{dx}{x} = -0.01 \int_0^{24} dt$$

$$x = 30,600 e^{-0.24} = 241,000 \text{ mg}$$

$$\text{Conc} = \frac{241,000}{(10,000)(3.785)} = [6.4 \text{ mg / liter}]$$

c. The maximum conc. in the tank is $[10 \text{ mg / liter}]$

Solutions Chapter 32

32.15

Basis: 1 day of operation 1440 min

Sr⁹² balance:Let $x = \text{kg Sr}^{92}$ in tank per kg H₂O at time t

Accumulation = In - Out - Decay

$$x|_{t+\Delta t} - x|_t = \frac{1.5 \times 10^{-3}}{\text{min}} \left| \frac{1.0 \times 10^3 \text{ kg H}_2\text{O}}{\text{m}^3} \right| \frac{1500 \text{ kg Sr}^{92}}{10^6 \text{ kg H}_2\text{O}} \left| \frac{\Delta t \text{ min}}{1} \right|$$

$$- \frac{1.5 \times 10^{-3} \text{ m}^3}{\text{min}} \left| \frac{1.0 \times 10^3 \text{ kg H}_2\text{O}}{\text{m}^3} \right| \frac{x \text{ kg Sr}^{92}}{\text{kg H}_2\text{O}} \left| \frac{\Delta t \text{ min}}{1} \right|$$

$$- \frac{0.693}{2.7} \left| \frac{1 \text{ hr}}{60 \text{ min}} \right| \frac{x \text{ kg Sr}^{92}}{\text{kg H}_2\text{O}}$$

$$\frac{dx}{dt} = (2.25)10^{-3} - 1.5(x) - 4.28 \cdot 10^{-3}(x)$$

Integrating between $t = 0$ and $t = 1440 \text{ min}$,

$$x = \boxed{1.5 \times 10^3 \text{ kg Sr}^{92} / \text{kg H}_2\text{O}}$$

Y⁹² balance:Let $y = \text{lb Y}^{92}$ in tank per lb H₂O at time t

$$\frac{dy}{dt} = (4.28)10^{-3}(x) - 1.5(y) - \frac{0.693y}{(3.5)(60)}, \text{ from which}$$

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$$y = \boxed{4.28 \times 10^6 \text{ kg Y}^{92} / \text{kg H}_2\text{O}}$$

Zr⁹² balance:Let $z = \text{lb Zr}^{92}$ in tank per lb H₂O at time t

$$\frac{dz}{dt} = \frac{0.693}{(3.5)(60)} y - 1.5 z, \text{ from which}$$

$$z = \boxed{9.39 \times 10^{11} \text{ kg Zr}^{92} / \text{kg H}_2\text{O}}$$

32.16

Assume isothermal process

Let $x = (\text{m}^3)$ in the tank at time t $V = (\text{m}^3)/\text{min}$ entering and leaving the tankMaterial balance on O₂ in terms of (m³) at T, 1 atm

$$\frac{0.21(\text{m}^3)}{(\text{m}^3) \text{ air}} \left| \frac{V(\text{m}^3) \text{ air}}{\text{min}} \right| \left| \frac{\Delta t \text{ min}}{1} \right| - \frac{x(\text{m}^3) \text{ O}_2}{3(\text{m}^3) \text{ gas}} \left| \frac{V(\text{m}^3) \text{ gas}}{\text{min}} \right| \left| \frac{\Delta t}{1} \right|$$

$$\text{Accumulation} = x(\text{m}^3)|_{t+\Delta t} - x(\text{m}^3)|_t$$

$$\int_3^x \frac{dx}{(0.21 - x/3)} = \int_0^t V dt = 9(\text{m}^3)$$

$$-3 \ln \frac{(0.21 - x/3)}{0.21 - 1} = 9$$

(continued)

$$x = 0.75 \text{ (m}^3\text{)}$$

$$\text{concentration} = \frac{9.75 \text{ (m}^3\text{)}}{3 \text{ (m}^3\text{)}} = 0.25$$

$$\text{or concentration} = \boxed{25\%}$$

32.17

Basis: 1 mol C_6H_{12}

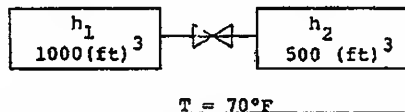
$$\frac{d(\text{C}_4\text{H}_8)}{dt} = K(\text{C}_6\text{H}_{12}) \quad \text{C}_6\text{H}_{12} = 1 - \text{C}_4\text{H}_8$$

$$\text{C}_6\text{H}_{12} = 1 - \text{C}_2\text{H}_4$$

$$\frac{d(\text{C}_2\text{H}_4)}{dt} = K(\text{C}_6\text{H}_{12}) \quad \frac{d(\text{C}_6\text{H}_{12})}{dt} = -K(\text{C}_6\text{H}_{12})$$

$$\boxed{\text{C}_6\text{H}_{12} = e^{-Kt}}$$

32.18



Let p_1, n_1 = pressure and number of moles of N_2 in the large tank at any time t
 p_2, n_2 = the corresponding values in the small tank.

Then, $dn_2/dt = K(p_1 - p_2)$

Initially $p_1 = 700, p_2 = 0; dn_2/dt = 0.2 \text{ kg mol/hr}$

$$0.2 = K(700 - 0) \text{ or } K = 2.857 \times 10^{-4} \text{ kg mol/(hr)(kPa)}$$

Initially, no. of moles is

$$n_1^0 = \frac{30 \text{ m}^3}{22.4 \text{ m}^3} \left| \frac{700 \text{ kPa}}{101.3 \text{ kPa}} \right| \left| \frac{273 \text{ K}}{293 \text{ K}} \right| = 8.62 \text{ kg mol}$$

Assume ideal gas law holds.

$$pV = nRT$$

$$p_1 = \frac{8.31 \text{ (kPa)(m}^3\text{)}}{(K)(\text{kg mol})} \left| \frac{293 \text{ K}}{30 \text{ m}^3} \right| n_1 = 81.2 \text{ } n_1$$

$$p_2 = \frac{8.31 \text{ (kPa)(m}^3\text{)}}{(K)(\text{kg mol})} \left| \frac{293 \text{ K}}{15 \text{ m}^3} \right| n_2 = 162.3 \text{ } n_2$$

$$n_1 + n_2 = 8.62$$

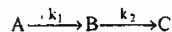
$$\frac{dn_2}{dt} = 2.857 \times 10^{-4} (700 - 81.2 \text{ } n_2)$$

Final moles in tank 2 will be $(15/30 + 15)(8.62) = 2.87$ hence

$$1/2 (2.87) = 1.44.$$

$$\int_0^{1.44} \frac{dn_2}{700 - 81.2 \text{ } n_2} = 2.857 \times 10^{-4} \int_0^t dt \quad t = \boxed{27.5 \text{ hr}}$$

32.19

Initial conditions: at $t = 0$, $C_A = C_{AO}$ and $C_B = C_C = 0$

$$\frac{dC_A}{dt} = -k_1 C_A \quad (1)$$

$$\frac{dC_B}{dt} = -k_1 C_A - k_2 C_B \quad (2)$$

$$\frac{dC_C}{dt} = -k_2 C_B \quad (3)$$

From Eq. (1),

$$\frac{dC_A}{C_A} = -k_1 dt; \quad \int_{C_{AO}}^{C_A} \frac{dC_A}{C_A} = -k_1 \int_0^t dt, \text{ or } \ln \frac{C_A}{C_{AO}} = -k_1 t$$

$$C_A = C_{AO} e^{-k_1 t} \quad (4)$$

$$\frac{dC_B}{dt} = k_1 C_A - k_2 C_B = k_1 C_{AO} e^{-k_1 t} - k_2 C_B$$

$$\frac{dC_B}{dt} + k_2 C_B = k_1 C_{AO} e^{-k_1 t} \quad (5)$$

which is the first-order linear differential equation of the form $dy/dx + Py = Q$. By multiplying through with the integrating factor $e^{\int P dx}$, the solution is

$$y e^{\int P dx} = \int Q e^{\int P dx} dx + \text{constant}$$

Applying this general procedure to the integration of Eq. (5), we find that the integrating factor is $e^{k_2 t}$. The constant of integration is found to be $-k_1 C_{AO}/(k_2 - k_1)$ from the initial condition $C_B = 0$ at $t = 0$, and the final expression for the variation in concentration of B is

$$C_B = C_{AO} k_1 \left(\frac{e^{-k_1 t}}{k_2 - k_1} + \frac{e^{-k_2 t}}{k_1 - k_2} \right) \quad (6)$$

If k_1 is much larger than k_2 , then

$$C_B = C_{AO} e^{-k_2 t} \quad (7)$$

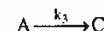
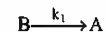
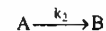
In other words, the concentration of B is determined by k_2 . Noting that for the constant-volume system there is no net change in total number of moles, we find the material balance at any time to be

$$C_{AO} = C_A + C_B + C_C$$

which with Eqs. (4) and (5) gives

$$C_C = C_{AO} \left(1 + \frac{k_2}{k_1 - k_2} e^{-k_1 t} + \frac{k_1}{k_2 - k_1} e^{-k_2 t} \right) \quad (8)$$

32.20



(continued)

$$\frac{dC_A}{dt} = -k_2 C_A + k_1 C_B - k_3 C_A = -(k_2 + k_3) C_A + k_1 C_B \quad (1)$$

$$\frac{dC_B}{dt} = k_2 C_A - k_1 C_B \quad (2)$$

$$\frac{dC_C}{dt} = k_3 C_A \quad (3)$$

Initial conditions: at $t = 0$, $C_A = C_{AO}$ and $C_B = C_C = 0$.

To solve Eqs. (1) – (3) use matrix operations

$$Q = \begin{bmatrix} -(k_2 + k_3) & k_1 \\ k_1 & -k_1 \end{bmatrix}$$

$$C^T = [C_A, C_B] \quad C(0)^T = [C_{AO}, 0]$$

To find the eigenvalues of Q we set

$$|Q - \lambda I| = \begin{vmatrix} -(k_2 + k_3) - \lambda & k_1 \\ k_1 & -k_1 - \lambda \end{vmatrix} = (k_2 + k_3 + \lambda)(k_1 + \lambda) - k_2 k_1 = 0$$

The roots are

$$\lambda_1 = \frac{-a + \sqrt{a^2 - 4k_2 k_3}}{2}$$

$$\lambda_2 = \frac{-a - \sqrt{a^2 - 4k_2 k_3}}{2}$$

where: $a = (k_1 + k_2 + k_3)$. Consequently the solution to the set of Eqs. (1) and (2) is:

$$C^T = [C_{AO}, 0] \left[\frac{Q - \lambda_2 I}{\lambda_1 - \lambda_2} e^{\lambda_1 t} + \frac{Q - \lambda_1 I}{\lambda_2 - \lambda_1} e^{\lambda_2 t} \right]$$

$$[C_A, C_B] = \frac{1}{d} [-C_{AO}(k_1 + k_3 + \lambda_2), C_{AO} k_1] - \frac{1}{d} [-C_{AO}(k_1 + k_3 + \lambda_1), C_{AO} k_1] \times e^{\lambda_2 t}$$

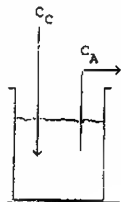
where: $d = \lambda_1 - \lambda_2$. Finally,

$$C_A = \frac{C_{AO}}{\sqrt{(k_1 + k_2 + k_3)^2 - 4k_2 k_3}} \left[-(k_1 + k_3 + \lambda_2) e^{\lambda_1 t} + (k_1 + k_3 + \lambda_1) e^{\lambda_2 t} \right] \quad (4)$$

$$C_B = \frac{C_{AO} k_1}{\sqrt{(k_1 + k_2 + k_3)^2 - 4k_2 k_3}} [e^{\lambda_1 t} - e^{\lambda_2 t}] \quad (5)$$

$$C_C = \frac{C_{AO} k_3}{\sqrt{(k_1 + k_2 + k_3)^2 - 4k_2 k_3}} \left[-(k_1 + k_3 + \lambda_2) \frac{e^{\lambda_1 t}}{\lambda_1} + (k_1 + k_3 + \lambda_1) \frac{e^{\lambda_2 t}}{\lambda_2} \right] \quad (6)$$

32.21

Tank A:

$$(1) \quad FC_C - FC_A = V \frac{dC_A}{dt}$$

$$(2) \quad FC_A - FC_B = V \frac{dC_B}{dt}$$

$$(3) \quad FC_B - FC_C = V \frac{dC_C}{dt}$$

$$F[=] \frac{\text{gal}}{\text{min}} = 50$$

$$V[=] \text{gal} = 1000$$

$$C[=] \frac{\text{lb}}{\text{gal}}$$

$$\Delta = \begin{bmatrix} -50 & 50 & 0 \\ 0 & -50 & 50 \\ 50 & 0 & -50 \end{bmatrix}$$

$$\mathbf{Y}^T = [C_A, C_B, C_C], \quad \mathbf{Y}^T(0) = [3, 0, 3]$$

$$\Delta - \lambda I = \begin{bmatrix} -50 - \lambda & 50 & 0 \\ 0 & -50 - \lambda & 50 \\ 50 & 0 & -50 - \lambda \end{bmatrix} = 0$$

$$0 = -(50 + \lambda)^3 + (50)^3$$

$$0 = (50)^3 - 3(50)^2 \lambda - 150 \lambda^2 - \lambda^3 + (50)^3$$

$$0 = \lambda [3(50)^2 + (150)\lambda^2 - \lambda^3 + (50)^3]$$

$$\text{roots: } \lambda_1 = 0$$

$$\lambda_{2,3} = \frac{-150 \pm \sqrt{22,500 - 30,000}}{2}$$

$$\text{when } t = 0, C_A V = 3000 \text{ lb}, C_C V = 3000, C_B V = 0$$

$$t_A = ?, C_A V = 2100 \text{ lb}; t_C = ?, C_C V = 2100 \text{ lb}; t_B = ?,$$

$$C_B V = 1900 \text{ lb.}$$

$$\text{Solve the equations to get } t_A = 22.8 \text{ min, } t_C = \boxed{28.2 \text{ min}},$$

$$t_B = 24.4 \text{ min}$$

32.22

Energy balance around the tank:

$$\frac{dU_T}{dt} = -\Delta(\dot{H}_m) \quad (1)$$

Energy balance around the heat exchangers:

$$0 = \frac{dE_H}{dt} = \frac{dU_H}{dt} = -\Delta(\dot{H}_m) + Q \quad (2)$$

We have assumed that the residence time of the liquid in the heat exchanger is very small and that kinetic and potential energy contributions are negligible. From Eqns. 1 and 2 we obtain

$$\frac{dU_T}{dt} = -Q \quad (3)$$

(continued)

Subscripts T and H refer to the tank and the heat exchanger, respectively. Because the liquid is approximately incompressible, $C_p \cong C_v$. Then, $dU_T = mC_v dT \cong mC_p dT$. Furthermore, the rate of heat addition to the liquid Q is given by $Q = U_o A_o (T - 180^\circ)$. The notation used here is the same as the one introduced in Problem 7.24. Hence, Eq. 3 becomes

$$mC_p \frac{dT}{dt} = -U_o A_o (T - 180) \quad (4)$$

$$\frac{dT}{dt} + \frac{U_o A_o}{mC_p} T = 180 \frac{U_o A_o}{mC_p} \quad (5)$$

Eq. 5 is a first-order linear differential equation. Its solution is

$$T \exp\left(\frac{U_o A_o}{mC_p} T\right) = 180 \frac{U_o A_o}{mC_p} \quad (6)$$

From the initial condition, $T = 60^\circ\text{F}$ at $t = 0$, the value of the constant is this: constant $= -120^\circ\text{F}$. From Eq. 6, the expression for t is

$$t = \frac{mC_p}{U_o A_o} \ln\left(\frac{120}{180 - 120}\right) = \quad (7)$$

For the data given,

$$t = \frac{(10,000)(1.0)}{(40)(300)} \ln\left(\frac{120}{180 - 120}\right) = \boxed{0.578 \text{ hr}}$$

32.23

a. We shall make the following assumptions:

1. Steam temperature remains constant in coil.

- Heat capacity of suspension does not change very much with change in temperature.
- Agitator maintains uniform temperature throughout.
- Heat-transfer coefficient is independent of position and time.
- The walls of the tank are adiabatic.

The unsteady-state macroscopic energy balance

$$\frac{d}{dt} E_{\text{tot}} = -\Delta \left[\left(\dot{U} + p\dot{V} + \frac{1}{2} \frac{\langle \dot{v}^2 \rangle}{\langle \dot{v} \rangle} + \dot{P} \right) m \right] + Q + W, \text{ where}$$

$E_{\text{tot}} = U_{\text{tot}} + K_{\text{tot}}$, reduces to

$$\frac{d}{dt} \Delta U_{\text{tot}} = -\Delta(\Delta \dot{H}m) + Q \quad (1)$$

because the kinetic and potential energy in the accumulation term and the work term W as well as the kinetic and potential energy terms may be neglected.

$\Delta U_{\text{tot}} = WC_p(T - T_o) \cong wC_p(T - T_o)$. Furthermore, the rate of heat addition to the system Q is given by $Q = \dot{U}A(T_s - T)$. Hence Eq. (1) becomes

$$wC_p \frac{d(T - T_o)}{dt} = \dot{U}A(T_s - T) - mC_p(T - T_o) \quad (2)$$

Multiplying through by $1/mC_p(T_s - T_o)$, Eq. (2) becomes

$$\frac{wC_p}{mC_p(T_s - T_o)} \frac{d(T - T_o)}{dt} = \frac{\dot{U}A}{mC_p(T_s - T_o)} (T_s - T) - \left(\frac{T - T_o}{T_s - T_o} \right)$$

(continued)

$$\frac{w}{m} \frac{d}{dt} \left(\frac{T - T_a}{T_s - T_o} \right) = \frac{\dot{U}A}{mC_p} \left(1 - \frac{T - T_a}{T_s - T_o} \right) - \left(\frac{T - T_a}{T_s - T_o} \right) \quad (3)$$

Introducing the dimensionless variables

$$\Phi = \frac{T - T_a}{T_s - T_o}, \quad n = \frac{m}{w} t, \quad B = \frac{\dot{U}A}{mC_p}$$

Eq. (3) becomes, $\frac{d\Phi}{dn} = B(1 - \Phi) - \Phi$, or

$$\frac{d\Phi}{dn} + \Phi(1 + B) = B \quad (4)$$

which is a first-order linear differential equation of the form

$$\frac{dy}{dx} + Py = Q$$

The solution to this equation is

$$ye^{\int P dx} = Qe^{\int P dx} + \text{constant}$$

Applying this principle to Eq. (4), we find that the integrating factor is $e^{(1+B)n}$. The constant of integration is found to be $-B/(1+B)$ from the boundary condition $n = 0$, $\Phi = 0$. The final expression for Φ , the reduced temperature is

$$\Phi e^{(1+B)n} = \left(\frac{B}{1+B} \right) (e^{(1+B)n} - 1)$$

the expression for n as a function of B and Φ is,

$$n = \left(\frac{1}{1+B} \right) \ln \left[\frac{B}{B - \Phi(1+B)} \right] \quad (5)$$

b. Numerical calculation.

$$T = 180^\circ\text{F}; \quad T_o = 120^\circ\text{F}; \quad T_s = 220^\circ\text{F}; \quad A = 23.9 \text{ ft}^2; \quad w = 6000 \text{ lb};$$

$$\dot{U} = 100 \text{ Btu/(hr)(ft}^2\text{)(}^\circ\text{F)}; \quad m = 1200 \text{ lb/hr}; \quad C_p = 1.0 \text{ Btu/(lb)(}^\circ\text{F)}.$$

$$B = \frac{(100)(23.9)}{(1200)(1.0)} = 1.99; \quad \Phi = \frac{180 - 120}{220 - 120} = 0.60$$

From Eq. (5) we find that $n = 0.777$.

$$t = \frac{nw}{m} = \frac{(0.777)(6000)}{1200} = \boxed{3.89 \text{ hr}}$$

c. If heat-transfer area is doubled, $n = 0.28$. thus,

$$t = \boxed{1.40 \text{ hr}}$$

Then, the greater the area available for heat transfer, the greater the amount of heat transferred to the suspension, and consequently, the less the time required for the effluent temperature to reach a given value.

32.24

We shall use the same nomenclature used in problem 7.23. The following assumptions are made:

1. Steam temperature remains constant in coil.
2. Density and heat capacity of water do not change very much with change in temperature.
3. Because the fluid is approximately incompressible.
 $C_p = C_v$.
4. Agitator maintains uniform temperature throughout.

(continued)

5. Heat-transfer coefficient is independent of position and time.

6. The walls of the tank are adiabatic.

We choose the fluid within the tank as our system. Kinetic and potential energy may be neglected in this position. Since the work term is zero and there is no outlet stream, $m_2 = 0$. Hence, for this system the energy balance reduces to

$$\frac{d}{dt} U_{tot} = m\dot{H}_1 + Q \quad (1)$$

which states that the internal energy of the system is increasing because of the addition of fluid with enthalpy H_1 and because of the addition of heat Q through the steam coil.

In view of the fact that U_{tot} and H_1 cannot be given absolutely, we now select the inlet temperature T_0 as the thermal datum plane. Then $\hat{H}_1 = 0$ and $U_{tot} = \rho C_p V(T - T_0) \equiv \rho C_p V(T - T_0)$. Furthermore, the rate of heat addition to the system Q is given by $Q = \dot{U}A(T_s - T)$. Hence Eq. 1 becomes

$$\rho C_p \frac{d}{dt} V(T - T_0) = \dot{U}A(T_s - T) \quad (2)$$

Now the instantaneous area and volume are simply related to the total available area and volume according to the relations

$$V(t) = \frac{mt}{\rho}; \quad A(t) = \frac{mt}{\rho V_0} A_0 \quad (3,4)$$

where $\rho V_0 / m = t_0$ is the time required to fill the tank. Substitution of these expressions in Eq. 2 gives

$$m\dot{C}_p t \frac{d(T - T_0)}{dt} + \dot{C}_p m(T - T_0) = \dot{U}A_0 \frac{mt}{\rho V_0} (T_s - T) \quad (5)$$

which is to be solved with the initial condition that at $t = 0$, $T = T_0$.

The following reduced variables are introduced now:

$$\phi = \frac{T - T_0}{T_s - T_0} = \text{reduced temperature} \quad (6)$$

$$n = \frac{t}{t_0} = \frac{mt}{\rho V_0} = \text{reduced time} \quad (7)$$

In order to rewrite Eq. 5 in terms of the foregoing dimensionless variables, the entire equation is multiplied through by $[1 / mC_p(T_s - T_0)]$ to obtain

$$\left(\frac{\dot{U}A_0}{mC_p} \right) \left(\frac{mt}{\rho V_0} \right) \left(1 - \frac{T - T_0}{T_s - T_0} \right) = \left(\frac{T - T_0}{T_s - T_0} \right) + t \frac{d}{dt} \left(\frac{T - T_0}{T_s - T_0} \right) \quad (8)$$

or

$$Bn(1 - \phi) = \phi + n \frac{d\phi}{dn} \quad (9)$$

in which $B = \dot{U}A_0 / mC_p$ is a dimensionless group appearing in the differential equation. The equation may be further simplified by noting that if the last term is multiplied by B/B then the reduced time variable always appears in the combination Bn , which combination is designated by α . Thus,

$$\frac{d\phi}{d\alpha} + \left(1 + \frac{1}{\alpha} \right) \phi = 1 \quad (10)$$

$$\phi = 0 \quad \text{at} \quad \alpha = 0 \quad (11)$$

is the final analytical statement of the problem. Eq. 10 is a first-order linear differential equation. Its solution is

$$\phi = 1 - \frac{1 - \exp(-\alpha)}{\alpha} \quad (12)$$

(continued)

where the constant of integration has been determined from the initial condition (11). Finally, the temperature of the liquid in the tank, when it has been filled, is given by Eq. 12 when $n = 1$ (or $\alpha = B$); in terms of the original variables, this result is

$$\frac{T_f - T_o}{T_s - T_o} = 1 - \frac{1 - \exp(-UA_o / mC_p)}{(UA_o / mC_p)} \quad (13)$$

For the data given in the problem,

$$B = \frac{(100)(32.9)}{(1200)(1.0)} = 2.74. \text{ For this value, Eq. (13) gives } (T_f - T_o) /$$

$$(T_s - T_o) = 0.659, \text{ whence } T_f = \boxed{155.5^\circ\text{F}}.$$

When the tank is half full, $n = 1/2$, $\alpha = \alpha / 2$. Thus

$$\phi = 1 - \frac{1 - \exp\left(-\frac{\alpha}{2}\right)}{\frac{\alpha}{2}} = -\frac{1 - 0.254}{1.37} = 0.455, \text{ whence}$$

$$T_f = \boxed{129.0^\circ\text{F}}$$

32.25

a. If heat losses from the top and the bottom of the tank are neglected, the resulting energy balance is

$$\rho VC_p \frac{dT}{dt} = \bar{U}A(T_s - T) \quad (1)$$

$$\int_{T_o}^{T_f} \frac{dT}{T_s - T} = \int_0^t \frac{\bar{U}A}{\rho VC_p} dt \quad (2)$$

or

$$= \ln[(T_s - T) / (T_s - T_o)] = \frac{\bar{U}A}{\rho VC_p} t \quad (3)$$

Numerical Calculations:

$$\frac{\bar{U}A}{\rho C_p V} = \frac{(40)(25\pi)}{(62.4)(1.0)(125\pi / 4)} = 0.513 \text{ hr}^{-1}. \text{ Since}$$

$T_s = 230^\circ\text{F}$, $T = 170^\circ\text{F}$, and $T_o = 70^\circ\text{F}$, the time necessary to raise the temperature of the tank contents to 170°F is given by Eq. 3. Thus,

$$t = \boxed{1.91 \text{ hr}}$$

b. If the heat losses from the top and the bottom of the tank are taken into account, the energy balance for the system is,

$$\rho VC_p \frac{dT}{dt} = \bar{U}A(T_s - T) + \bar{U}_o A_o (T_{\text{air}} - T) \quad (4)$$

where $\bar{U}_o$ = overall heat transfer coefficient for both the top and the bottom of the tank. If we let $a = UA + U_o A_o$ and $K = UAT_s + U_o A_o T_{\text{air}}$, Eq. 4 becomes

$$\frac{\rho VC_p}{a} \frac{dT}{dt} = \frac{K}{a} - T \quad (5)$$

and when integrated we obtain the following equation:

$$-\ln\left(\frac{K - aT}{K - aT_o}\right) = \frac{a}{\rho VC_p} t \quad (6)$$

For the data given in this problem,

$$a = (40)(25\pi) + (10)(25\pi / 2) = 3540 \text{ Btu} / (\text{hr})(^\circ\text{F})$$

$$K = (40)(25\pi)(230) + (10)(25\pi / 2)(70) = 7.50 \times 10^5 \text{ Btu/hr.}$$

$$\text{Thus, } t = \boxed{2.10 \text{ hr}}$$

SOLUTIONS TO THOUGHT PROBLEMS

Section 1.1

1. This is a fuzzy problem because many volume units called barrel exist:

British dry = 36 gal
Cranberry = 5826 in³
Oil = 42 gal
US dry = 105 quarts
US liquid = 31.5 gal

Section 1.3

1. a. Gravity is not a force, it is an acceleration. Weight is a force.
b. In SI a person has mass in kg but weight in Newton's even though common usage may use kg for weight.
c. Use of such a conversion factor implies that a relation exists between g and °C, which does not exist. It is ok to write: 1.00 g water/1.00 cm³ water, because a relation between water and cm³ water does exist.
2. Not really, because kg is not a unit of force; kgf is commonly used nevertheless.

Section 1.4

1. No. You can only determine that the equation has consistent terms.
2. The units are wrong.

Section 1.5

1. (a) Yes; (b) Not if measured with an error of 1/8 inch, but ok if 6 5/8 is exact.
2. No, because it is an exact number. The answer is good to three significant figures.
3. You know that 100mL can be measured easily to 3 or 4 significant figures.

Section 2.1

1. If the question refers to mass, the answer is yes. If the answer refers to any other measure, such as moles, the answer is no.
2. The question is: are the holes entities? The answer is yes.

Section 2.2

1. Would not sink because the overall density of the ship including the oil is less than that of sea water.
2. The density of hot water is less than that of cold water hence the container might not hold a gallon of hot water whereas it would hold a gallon of cold water or milk.
3. The density of gasoline is 0.81 and that of pentane 0.69. On more than one occasion tanks have overflowed because the contents were replaced by a liquid of lower specific gravity. The operators did not realize that the level indicator measured weight, not volume.

Section 2.3

1. Most organic bromides or iodides can be dissolved in a suitable organic solvent and a solution with the proper specific gravity to discriminate between the jades and arbite, serpentine, and other imitators of jade. For example, methylene iodide (sp. gr. = 5.7) is a liquid at room temperature and can be blended with ethanol to give a harmless liquid of the desired specific gravity.

Chapter 3

1. Follow the regulations of the U.S. Department of Agriculture which has proposed a strict permit system that, through tamper-proof computerized controls, assures that elevator operators adhere to Agriculture Department standards. Alternatively, grain could be priced at its dry weight on an industry wide basis (which is not currently done).

Chapter 4

1. The temperature probably is just a conversion from 2700°F, hence the answer is 2.
2. Examine Figure 4.2 for suggestions.
3. The thermocouple well was set only one inch into a 48 inch pipeline. When it rained, the exterior of the pipeline, and the thermocouple, would cool, causing a furnace to heat the residual going into the pipeline, excessively as it turned out.

Section 5.1

1. What counts is pressure, not force. On a floor the contact area with your body is small, so the pressure at the contact points is larger than experienced on a sofa.
2. When the water rushes through the tube its inertia is sufficient to carry it above bend B and start the siphon working.

Section 5.2

1. The essential point is that the covering paper can bulge out a bit so that the air pressure inside the glass is lowered. The pressure difference keeps the water in place. The water in the glass is compressed by the air. A glass plate on top of the completely filled glass is acted upon by the external air pressure and an equally large force from the compressed water on the other side. Thus, there is no pressure difference to support the weight of the water in the glass.
2. The tank, like most such tanks, was designed for a vacuum of 2 ½ inches water gauge only (0.1 psi or 0.6 kPa), and would collapse at a vacuum of about 6 inches water gauge (0.2 psi or 1.5 kPa).

If the tank had been filled instead of emptied it might have burst because it was designed to withstand a pressure of only 8 inches water gauge (0.3 psi or 2 kPa) and would burst at about three times this pressure. Whether it burst or not would have depended on the depth of water above the end of the hose.
3. The answer surprisingly is yes! Such pressures exist all around us-the pressure of sap in trees often gets as low as -2 MPa. Pressures as low as -20 MPa have been obtained in water in the laboratory.

When discussing pressure in gases, we often define the pressure as "the sum of impulses transferred to the wall of a container per unit time and area". By this definition, pressures lower than a vacuum could not be produced. For pressures to be lower than a vacuum, our molecular interpretation would have to include attractive forces between the molecules of the fluid and the walls of the container. Such forces are typical of liquids but not of gases.

Attractive and repulsive forces between molecules correspond well to the macroscopic concepts of tension and compression. If we consider material with normal stresses lower than the pressure of a vacuum to be under tension and compression. If we consider material with normal stresses lower than the pressure of a vacuum to be under tension and material with normal stresses higher than the pressure of a vacuum to be under compression, then one way to distinguish liquids from gases is that liquids are fluids that can sustain compression or tension and gases are fluids that can sustain only compression. A lucid description of osmotic pressure is presented by Hammel and Scholander (H.T. Hammel and P.F. Scholander, *Osmosis and Tensile Solvent* (Springer Verlag, Berlin, 1967), pp. 1-73.)

4. During the fall, the force on the water exerted by gravity drops to zero.

Section 6.1

1. Energy, linear momentum, angular momentum, electric charge are some.
2. No. The totals of the withdrawals are valid outputs but the totals of the amount left are meaningless.

Section 6.3

1. By the conservation of mass in the closed system, the answer is d.
2. A pipe connected to system at the desired level (to retain some liquid) connected to an orifice operating in parallel with the controller will allow liquid to pass if the controller ceases to separate.

Section 6.4

1. The frozen orange juice was not completely removed from the tank truck on discharge, and this residual was dumped into the lake on cleaning the tank on return to Florida.

Section 7.2

1. The material balances are:

$$\begin{aligned}
 (1) \quad & 0.10(10) + 0.30(6) = 0.175(16) \quad \text{checks, and does not contain unknowns} \\
 (2) \quad & 0.90(10) + 0.50(6) = w_1'(16) \quad \text{is uncoupled} \\
 (3) \quad & 0.0(10) + 0.20(6) = w_2'(16) \quad \text{is uncoupled} \\
 (4) \quad & 1 = 0.175 + w_1' + w_2'
 \end{aligned}$$

Only two unknowns exist if you introduce equation (4) into (1) - (3). The rank of the coefficient matrix of (2), (3), and (4) is 2, hence the problem has a unique solution.

Chapter 8

1. You can detect counterfeit gold or silver by weighing and measuring a coin or bar against the issuing mint's specifications. Modern counterfeiters may have mastered the appearance of their fakes but the principle of density—the ratio of mass to volume—has not changed. Gold has a greater density than the common metals such as lead, brass, copper and steel. This means that it is impossible to make a common metal fake identical to a genuine coin in both weight and size from these metals.

References	gold	Silver	copper	lead	iron	nickel	zinc
Perry	19.30	10.49	8.93		11.33	7.86	7.135
CRC	18.88	10.50	8.96		11.35	7.87	7.133
S & E of materials (Askeland)	19.30	10.49	8.93		11.36	7.87	7.133
Himmelblau	--	--	8.92		11.34	7.70	7.140

Silver can be imitated, but if made of a lead/tin alloy it would be too soft. Use 79.1% Pb, 20.9% Sn.

2. If the ash in the sludge is identical to the ash in the residual ash, then on the basis of 100 kg of sludge:

$$\frac{67 \text{ lb ash}}{100 \text{ kg sludge}} \left| \frac{100 \text{ kg residual ash}}{87 \text{ lb ash}} \right| \frac{184 \text{ mg of Cd}}{1 \text{ kg residual ash}} = 142 \text{ mg}$$

This number can be compared with 169 kg in the sludge so that $169 - 142 = 27 \text{ mg}$, (16%) is lost up the stack if the assumptions made hold.

Similarly for Pb, compare 307 mg with 412 mg in the sludge, and for Zn compare 1496 mg with 1554 mg. Not all of the heavy metals end up in the residual ash.

Section 9.1

- The residual material on the metal surface reacted with oxygen and reduced the oxygen content of the residual air.
- One gallon of crude oil at room temperature is about 3000g or 6 to 30 g mol of oil that requires for complete combustion 3 to 15 g mol O_2 . The seawater with 10 ppm O_2 contains in 3×10^6 gal about 35g mol O_2 which agrees roughly with the statement in the article.
- Calculation shows the statement to be wrong. If the average car gets 25 miles per gallon, 26,000 miles corresponds to an output of about 11 tons of carbon dioxide. It has been estimated that a young apple tree produces about 44 lb of sugar per growing season, which is equivalent to an uptake of about 66 lb of carbon dioxide. Thus even 100 young apple trees would not remove the carbon dioxide produced annually by an average car until the trees had grown to more than twice their size when planted.

Section 9.2

- A gas was in the black cylinder and reacted with the material in the facepiece.

Section 10.3

- A service engineer from the manufacturer was called to test the combustion controls and found that the flue gas contained no excess oxygen and approximately 4% combustible gas. The ratio of combustion air to fuel was increased until the flue gas contained zero percent combustible gas and then the steam flow increased to the full 120,000 lb per hour capacity. In determining the cause of the combustion control malfunction, it was found that moisture from the products of combustion had condensed in the piping to the combustion air flow controller causing erroneous action. To eliminate this problem, an oxygen and combustible recorder was installed and a regular maintenance contract was

set up with the combustion control manufacturer. The installed cost of the new control equipment was \$95,000 vs. a loss of \$54,900 in fuel in the two months.

2. Fossil fuels contain more carbon than hydrogen. This is especially so for coal (over 95% of our fossil-fuel supply).

We prefer gaseous and liquid rather than solid fuels. So, there has been much effort to develop processes that convert coal, or waste materials, to gaseous and liquid forms as supplements to natural gas and petroleum. In all these processes, the main technical consideration has been to lower the carbon-to-hydrogen ration, by adding hydrogen.

Superficially, it might seem that this increase in the relative amount of hydrogen in the fuel would lessen CO₂ emissions. But that is not the case, because the production of the hydrogen itself inevitably consumes more energy (derived from carbon-containing fuel) than is subsequently regained when the hydrogen in the synthesized fuel is burned. In short, there is a net addition of carbon dioxide to the atmosphere.

Gases from coal, cellulose, and other waste materials via most of the known processes contribute 10 to 200 percent more carbon dioxide than would pure carbon for the same heat availability. The story is analogous with respect to ethanol as an alternative automotive fuel: In the absence of free ethanol, any process to manufacture that alcohol would give off at least twice as much CO₂ as would the use of gasoline, instead of ethanol, in the vehicle. It is true that using ethanol in automobiles gives off less carbon monoxide, but this is perhaps overshadowed by the danger posed by CO₂.

Another point should be made. Analysis shows that all of the synthetic fuels are intrinsically less efficient (based on actual heating value vs. that theoretically obtainable from the fuel's constituents in elemental form) than the fuel forms as they occur in nature.

Chapter 11

1. (1) Select a system with the smallest number of unknowns. (2) Select a system for which the data is the most accurate (3) select a system at the beginning of a sequence (or at the end).

Section 12.2

1. To protect the pump, a minimum-flow line (line with an orifice) normally is created leading from the pump's main discharge line back to the suction tank.

Section 13.1

1. The loss of free oxygen is more or less compensated for by reaction products such as CO and CO₂ (and also H₂O which, however, condenses). The important observation is that the water level inside the glass does not rise gradually. As the gas inside the glass is heated by the candle, the gas pressure increases and gas leaks out. (Some hot air is also caught in the glass as it is lowered towards the candle.) When the candle goes out, the gas cools off rapidly, its pressure decreases, so that water is forced into the glass.
2. In fact, this statement is wrong, and is wrong regardless of how one interprets the word "empty". If empty means evacuated or containing helium at one atmosphere pressure, then it is obviously untrue. On the other hand, if empty means containing *air* at one atmosphere then it is still untrue, although only slightly. The can has a volume of about 43 cubic inches and when full is said to contain 0.21 cubic feet of helium, the air inside would still weigh a bit less than the compressed helium.

Two possibilities for this error suggest themselves. One, the author of the statement neglected to carry out the computation, and just guessed (wrongly) that the compressed helium would have a mass less than the same can full of air at atmospheric pressure. Another explanation possible is that the author misunderstood the nature of buoyancy, and fell into the trap of thinking that since "helium rises," it will exert an upward (buoyant) force from inside the can and cause it to feel lighter than if the can contained air or even a vacuum.

3. Either p, V, n, or T would have to be rescaled, and the rescaled variables would not be compatible with the underlying definitions of the variables as used in other calculations. For example, T could be rescaled as $T^* = 8.314T$ if the usual $R = 8.314 \text{ J/(g mol) (K)}$ was revised to a value of R equal 1 J/(g mol) (K) .
4. No. The change in buoyancy caused by the decrease in volume has to be taken into account. The small volume displaces less air, and this volume is equivalent to the volume of escaped air. No weight loss should be observed.

Chapter 14

1. Rust had jammed the valve so that it could not be fully closed. Cl_2 at high pressure leaked through the valve when the regulator was removed. Apparently the regulator was defective and did not show the Cl_2 pressure.
2. Yes. The initial pressure is 1 atm. If the liquid expands by 1%, the gas volume is composed to 0.04L. The pressure rise of the gas bubble (assuming ideal gas) is 100 atm. Something on a normal piping system will blow.
3. Yes.
4. At the bottom of the well the pressure is 1400 psi (9600 kPa) and the temperature reaches 530°F (277°C). Oxidation takes place without boiling which would make it very difficult to clarify the effluent after oxidation. Also, the oxygen concentration in the water is much higher at 1400 psia.

Chapter 15

1. The main reason for the higher temperature is that Venus is closer to the sun than the earth. Venus receives more energy per unit area per unit time. The cause of the high pressure is not understood. The high temperature might cause an increase about 2.5 in the pressure, and the CO_2 vs. air might be another factor of 1.5. However, the gravity of Venus is about 0.8 that of earth. The net effect of the three factors would be only $2.5 \times 1.5 \times 0.8 = 3$. The actual state on Venus requires a molar specific volume of about 1L/g mol vs. 30L/g mol on earth.
2. The advantage is that the proteins are not exposed to organic solvents, heat, or oxygen, and retain their biological activity. Also, inasmuch as the process is supercritical, the solubility of the proteins in, say CO_2 , is good, and the disposal of the solvent is easy.

Section 16.1

1. At 144°C the liquid butadiene would have expanded to fill the tank, but tests showed that the tank would expand enough so that it would not rupture at 160°C. Further tests showed that a dimerization of butadiene to vinyl cyclohexene (an exothermic reaction initiated at 100°C) would produce a rapid rise in temperature to over 500°C, hence the pressure exceeded the bursting pressure of the tank.

2. Vaporize the liquid through a valve. Look at the CO_2 chart in Appendix J. Proceed downward from saturated liquid at 60°F (and high pressure) to 1 atm. A mixture of solid and vapor exists at low temperature.
3. The process is technically feasible (but not economically reasonable) by compressing the vapor above the critical point of water, producing a fluid, and then reducing the pressure. Refer to the SI diagram for water in the foldout in the back of the book.

Section 17.1

1. In combustion calculations we estimate the quantity of dry air required to burn a given amount of fuel. In reality, the atmospheric air is never dry; it consists of some moisture, depending on the relative humidity and dry bulb temperature. To compute the partial pressure of water vapor in the flue gas, which is required for calculating nonluminous heat transfer, we need to know the total quantity of water vapor in flue gases, a part of which comes from the combustion air. Also, when atmospheric air is compressed, the saturation vapor pressure of water increases, and if the air is cooled below the corresponding water dew point, water can condense. The amount of moisture in the air or gas fixes the water dew point, so it is important to know the amount of water vapor in the air or flue gas.

Section 17.2

1. The probe can work well in a dilution range from 2 to 1 to 20 to 1. The effect of fluctuations of the stack pressure can be less than 6%. A glass wool plug should be used to filter out particulates. Because of error involved in the dilution, the error in gas analysis is magnified.

Section 17.3

1. The gasoline dissolved in the water in the tank to its equilibrium concentration, but the equilibrium concentration when in contact with air is quite different—much lower—than in water, hence when in the sewer, gasoline left the water as a vapor and a spark started a fire.
2. The cold liquid condensed the stem in the tank, and the pressure in the tank was lowered so rapidly that the air flow through the vent was not enough to prevent a partial vacuum from forming in the tank sufficient to collapse it.

Section 18.1

- Possible causes are:
 - Diffusion and convection of air (oxygen) could take place through the open manhole during lunch.
 - Some of the CS_2 vapor might condense allowing air to pass into the tank.
 - N_2 and CS_2 might cool and allow air to flow in.
- The National Transportation Safety Board determined that the probable cause of the initial and subsequent explosions was the ignition of benzene vapors which were present both within the open cargo tanks and on the main deck of the tankship. The investigative record in this case does not contain sufficient information to determine the ignition source of the initial explosion. The probable source of ignition of the subsequent explosions was the heat produced from the preceding explosions.

As benzene cargo was discharged from the V. A. FOGG at the Phillips Petroleum Company and Dow Chemical Company terminals, air replaced the liquid benzene. The evaporation of the benzene residue which remained on the walls and bottom of the cargo tanks ensured a mixture of benzene vapor and air in the tanks. The lower and upper explosive limits of benzene vapor in air are 1.4 and 8.0 percent by volume, respectively.

Using the estimated air and water temperatures which affected the V. A. FOGG on February 1, it was determined that the benzene vapor concentration in the cargo tanks probably ranged between 5.7 and 8.0 percent.

Section 18.2

- If the water is continually condensed from the air by the coils in the refrigerator, there is good air circulation, and the water and vapor are in equilibrium on the coils, the air can be close to being saturated if the coils are not at a sufficiently low temperature (and may not be satisfactory generation). 100% saturation could result in water condensation on surfaces and food in the refrigerator.
- The answer to the question is satisfactory.

$$\text{Density} = \frac{\text{mass}}{\text{volume}} = \frac{(n)(MW)}{V}$$

$$\text{Density of air} = \frac{n_1(y_{\text{H}_2\text{O}}MW_{\text{H}_2\text{O}} + (1 - y_{\text{H}_2\text{O}})MW_{\text{air}})}{V} = \frac{n_1}{V}(y_{\text{H}_2\text{O}}(18) + (1 - y_{\text{H}_2\text{O}})(29))$$

On day 1, $y_{\text{H}_2\text{O}} > y_{\text{H}_2\text{O}}$ on day 2

On a humid day the air is less dense. The "heavy" or "muggy" feeling of the air occurs because of reduction of evaporation from the surface of the skin.

Section 19.2

- The tanks were not blanketed with nitrogen and there was an explosive mixture of naphtha vapor and air above the liquid in the tanks. The source of ignition was static electricity. The pumping rate was rather high so that the naphtha flowing through the pump and lines acquired a charge. A spark passed between the liquid in the tank and the roof or walls of the tank, igniting the vapor-air mixture.

There are several ways to preventing similar explosions:

- Use nitrogen blanketing or floating roof tanks
- Use anti-static additives; they increase the conductivity of the liquid so that charges can drain away rapidly to earth (provided equipment is grounded). However, make sure that the additives do not deposit on catalysts or interfere with chemical operations in other ways.
- Minimize the formation of static electricity by keeping pumping rates low (less than 3 m/s for pure liquids but less than 1 m/s if water is present) and avoiding splash filling. Filters and other restrictions should be followed by a long length of straight line to allow charges to decay.
- This dry ice jet contains solid and gaseous components. Two categories of cleaning exist, one for removing solid particles and one for hydrocarbons. In the former, particles are dislodged and removed by a combination of the gas aerodynamic drag force and collisions between the solid CO_2 snow and the surface particles. Collisions between the snow and surface particles are believed to be responsible for the snow removing particles of all sizes, micron and submicron.

In the case of hydrocarbons adhered to the surface, liquid carbon dioxide forms by the pressure increase when the snow impacts the surface. Fortunately, the triplet point of CO_2 is only at four atmospheres pressure, and hydrocarbons are known to be soluble in the liquid.

- The vapor pressure of a gasoline is 14.7 psia at 130°F.
 - The vapor pressure of a particular mixture of water and furfural is 760 mm at 99.9 °C.

4. If the vapor of the fluid being loaded dries all of the air out of the tank, the only vapor left is the vapor of the liquid, and its vapor pressure may be less than the atmospheric pressure outside the tank. Coast Guard regulations require that pressure sensors be installed near the hose connection at the dock, and systems (vacuum breakers) be installed to inject inerting or diluting, or enriched, gas into the vapor space.

Chapter 20

1.
 - a. Improved separation.
 - b. More economic separation (less energy used); less operating and/or capital costs for the process
 - c. Safety
2.
 - a. Application of heat
 - b. Change in pressure
 - c. Replace with a different fluid or gas

Section 21.1

1. The data gives $151,000 \text{ gal}/(\text{mi})^3$. Assume land used for crops is $738 \times 10^3 \text{ mi}^2$. 10.7% would be used for ethanol production.
2. About $3 \times 10^9 \text{ bbl oil/yr}$ are used; 10% is $3 \times 10^8 \text{ bbl}$. $3 \times 10^8 / 3.26 = 9 \times 10^{11} \text{ tons coal}$. If $6.5 \times 10^8 \text{ tons of coal}$ are mined each year, the fraction is 14%.
3. A 10 ft diameter windmill in a 20 mph wind will generate about $\frac{3}{4} \text{ hp}$ (0.5 kW) and cost about \$6000 including a 30 ft tower. The cost of the interest at 10% and the repayment of the \$6000, and maintenance is about \$3000 per year over 5 years. You have to determine the hours of operation and use of the electricity, i.e. pumping water that can be stored vs. operation of lights. Most likely your father will have to connect to the utility.

Section 21.2-1

1. Yes, but not for ever (See Nature, Vol. 364, 15 July, 1993, p.195).
2. The power transmitted by the drive shaft of the car can be measured when torque is applied and the shaft rotations per unit time counted: $\dot{W} = 2\pi nT$, where $\dot{W}$ is the power, n is the number of rotations/min, and T is the torque ($F \times r$). n is easy to read from the car instruments, but T requires a special instrument.

Section 21.2-2

1. The feeling of the 'degree' of heat or cold when our bodies touch some object is determined by the amount of heat which is given out, or is received by our bodies in unit time. The thermal conductivity of metal is greater than that of wood. If the metal and the wood are heated to the same temperature, higher than the temperature of our bodies, the metal will transmit to our bodies, on contact with them, more heat in unit time than will the wood. And if the metal is colder than our bodies, it will take from our bodies in unit time more heat than wood at the same temperature will. Therefore in the first case metal will seem hotter than wood, and in the second case it will seem colder. Plainly, it is when the metal and the wood are both at the same temperature as our bodies, and when there is no transference of heat, that they will seem equally heated to our touch.
2.
 - (a) As an example, ice melts at 0°C only if the necessary amount of heat be imparted to it – about 330J to every gram of ice – while water will only freeze if the same amount of heat is taken from it. Therefore if the vessel is not heated or cooled from outside, the water will not freeze and the ice will not melt. A mixture of water and ice at 0° will be in physical equilibrium.
 - (b) Fire walking illustrates the difference between temperature and heat. A temperature can be extremely high (900 to 1000 K perhaps for embers), but little heat is transferred to the feet because the heat capacity and conductivity of the embers are low, the time spent in contact with the embers is short, and after a time the temperature of the coals can drop considerably.
3. After the water in the jar and the water in the pot reach equilibrium at 1 atm and 100°C , heat transfer from the stove burner occurs only to the water in the pot, hence the water in the jar remains at 100°C without boiling. (A little vaporization does occur so that a small amount of heat is transferred from the water in the pot).

Section 21.2-4

1. The potential energy is converted to kinetic energy (and a little angular energy), hence no violation occurs.

Section 21.2-5

1. Some processes are unsteady-state batch, and the internal energy term in the energy balance then is involved.

Section 23.1

1. Steps to take:
 - (1) insulate tank (but see (7) below) but it may aid corrosion, hinder inspection
 - (2) cover tanks with earth (same problems as (1))
 - (3) emergency depressurize systems and pipe (expensive)
 - (4) liquid withdrawal/transfer system (only if very rapid – makes tank more vulnerable)
 - (5) keep tank full so $\int C_p dT$ absorbs heat transfer
 - (6) admit water into tank to replace vapor/liquid losses (can over pressurize, extensive venting)
 - (7) apply water spray (must be where needed)
2. Steam condensate had collected on the surface of the first batch of tar, and when the hot tar was pumped in on top of it, the water vaporized forming a large volume of steam that ejected the tar out of the tank.

Section 23.2

1. Before they reach the ice temperature they will transfer heat to the ice at different rates, but after they reach the ice temperature, heat transfer will stop and the ice will no longer melt.
2. You can write

$$dH - dU = d(pV) = pdV + Vdp$$

and show

$$C_p - C_v = \left(\frac{\partial H}{\partial T} \right)_p - \left(\frac{\partial U}{\partial T} \right)_v = \left(\frac{\partial U}{\partial V} \right)_T \left(\frac{\partial V}{\partial T} \right)_p + p \left(\frac{\partial V}{\partial T} \right)_p$$

The term on the right hand side is not zero. $(\partial V/\partial T)_p$ can be evaluated from the coefficient of thermal expansion $(1/V)(\partial V/\partial T)_p$, $(\partial U/\partial V)_T$, the internal pressure, is hard to find but can be calculated from the coefficient of thermal expansion; $(\partial V/\partial T)_p$ is the compressibility. Examples of such calculations give the following errors for $[(C_p - C_v)/C_v]$ 100: Hg, 12.7%; CH_3OH , 22%; C_6H_6 , 30%; Ag, 4%.

3. Refer to the answer to TP22.2-2.
4. If the gas is ideal, $\Delta H = Q$ is a function of temperature only so that there will be no difference. But if the gas is not ideal, the terms in the expression for the enthalpy $\Delta H_{3, \text{atm}} = \Delta H_{T_1}^T(1 \text{ atm}) + \Delta H_{1, \text{atm}}^{3, \text{atm}}(T_2) + \Delta H_{1, \text{atm}}^{3, \text{atm}}(T_1)$ must be evaluated for the particular gas.

Section 24.1

1. The side in the shade in the afternoon when the demand on the air conditioning system is the greatest, because the air intake will be cooler than on the sunnyside.
2.
 - a. No
 - b. No. Oversudsing consumes more energy.
 - c. No. Warm room air is pulled up the chimney.
 - d. Yes. The room will need to be cooled down when you return, but you'll still save energy.
 - e. Yes, but be sure the gas is off, too, and that the pilot light is relit before you turn the furnace back on.
 - f. No. An average shower saves about 5 gallons of hot water compared with a bath, or (if daily) almost 2,000 gallons of hot water a year.
 - g. No. Long-life bulbs are not energy-savers.
 - h. Yes. A 40-watt fluorescent gives off 80 lumens per watt, while a 60-watt incandescent yields only 14.7 lumens per watt.
 - i. No. The range will heat the refrigerator.

- j. Yes. Driving 55 saves about 20 percent.
- k. No. These accessories all consume energy.

Section 24.4

- Liquid is sometimes transferred from one tank to another by gravity. Overflowing has occurred when liquid flows from a tall tank to a short one. Overflow can occur when liquid is transferred from one tank to another of the same height several hundred yards away because a slight slope in the ground is sufficient to cause the lower tank to overflow.
- Aside from possible *practical* difficulties (such as the height of the tower): questions are:
 - Will the system run as described?
 - If so, does it constitute perpetual motion; or, if not, from what source does the energy come?
 - If it would not run, point out any fallacy in the reasoning above.

The answer to the perpetual motion problem is that the work needed to expand the hydrogen and oxygen is at least equal to the energy developed by the turbine; the fact that the water is electrolyzed does not significantly change the problem from one in which two pistons are moved away from one another inside a cylinder, creating a vacuum between them. In both cases a pressure is exerted through a volume. The machine will not run. Assuming that the water is of negligible volume, that W pounds of water are being used, that the air is of constant density ρ , and that the air stops at the top of the column whose height is H , then the energy developed by the turbine is given by WH , and the weight of air which must be displaced must equal the weight of the water W . If the volume is air is V .

$$V = W, \text{ or } V = W/\rho$$

The work done in expanding the air is the volume through which the air is expanded times the pressure: Work = $W/\rho \times H\rho = WH$.

This is the same as the work developed by the turbine. Actually, of course, the assumptions about the characteristics of the air are not strictly correct, but the same result

could be obtained (with considerable more work) by finding $\int_{h-a}^h p dV$.

- Turn off the fuel burners and let the furnace cool to 1600°F (energy used = 0 MBtu). Reheat from 1600°F to 2200°F in 2.6 hours (energy used = 70 MBtu). Hold at 2200°F for 0.5 hours (energy used = 5.1 MBtu). Total energy used = 75.1 MBtu vs (10.2) 8 = 81.6 MBtu by holding at 2200°F.

Section 25.1

- $\Delta \hat{H}_f^\circ$ is negative for the Al reaction and positive for the Cu reaction, hence heat has to be provided for the latter to occur.
- The stoichiometric ratio of the air to the fuel is so low that the mixture delivered to an engine designed for gasoline will not fire. In addition, much more heat transfer is required to vaporize the fuel. Also, the fuel injection system would have to be redesigned to use straight alcohol.

Section 25.2

- The energy balance is

$$m_E(4000 \text{ J/g}) = m_L C_L(T_L - T_V) = m_W \Delta H_{vap}$$

$$m_E/m_L \text{ is about } 1/4.$$
- To produce the H_2 via current technology, CO_2 is released. Production of H_2 by electrolytic decomposition of water requires 3000 Btu of fossil fuel to generate the necessary electricity to deliver 1000 Btu of energy via combustion of H_2 in a fuel cell. Steam reforming of natural gas requires 1500 Btu of fuel to do ditto. In each case CO_2 emissions occur greater than the direct use of the fuel for heat.

Section 25.3

- Dimethyle ether added to gasoline would not be safe. The vapor pressure of dimethyl ether at 20°C is 5 atm whereas the vapor pressure of octane is about 10 mm Hg. Its practical use is nil. Problems occur in automobiles (corrosion, vaporization, etc.). On the other hand, miles per gallon of a fuel is the important consideration and it is not proportional to calorific value. The Bank of America recorded millions of miles driven by its fleet of hundreds of cars, and showed that methanol blends increase mileage, as

would be expected from the much greater efficiency of methanol in an engine that, however, was designed to use gasoline. Performance in terms of miles per million Btu in the blends is better than gasoline.

Section 25.4

- 1 The improper design, operation, or use of thermal combustion systems may pose a threat to public health through emissions of potentially hazardous components of the wastes or their combustion byproducts. Incinerators can remove 99.99% of the hazardous waste occurring at concentrations > 1000 ppm in the feed, but incomplete combustion products indicate decomposition is not complete, and some of the intermediate products of combustion are also hazardous. The handling of the feed requires care as inadequate atomization and overfeeding leads to CO, unburned hydrocarbon, and difficult to detect hazardous species. A good reference is Science, vol. 206, p. 781-795 (1979); there are innumerable others. Gasohol is about at the break even point. Whatever assumptions are made about the use of crop residues, substitution of coal for oil in the processing, etc. affect the conclusions.
- 2 The diluent acts as an "energy absorber" so that for a fixed amount of heat transfer, the temperature of the exit products will be lower. Think of N₂ in the air.
- 3 None. The standard heat of reaction is defined for one mole at 25°C that reacts completely.
- 4 Gas turbine exhaust gases typically contain 14 to 16% oxygen, hence there is no need for additional oxygen to fuel such gas. However, if the amount of fuel (gas, oil, coal) is very large relative to the turbine exhaust, then additional oxygen may be needed.

Section 26.2

- 1 If efficiency is defined as $Q/\Delta H^\circ_{\text{rxn}}$, each of the quantities Q and $\Delta H^\circ_{\text{rxn}}$ should be based on comparable amounts of fuel (or perhaps costs of fuel would be best?), such as unit mass or mole, be at the same standard state, and refer to the same ambient conditions. Whether the amount of excess air can be the same is uncertain, but if it is not or even if it is, the gaseous product composition will differ in each case, e.g., using CH₄ vs. CH_{1.8} fuels. The overall heat capacities will only slightly differ, but the water vapor content may differ per mole of CO₂ produced. To avoid condensing the water vapor, the natural gas products cannot be cooled as much as fuel oil combustion products.

- 2 Acetone has a much higher vapor pressure than gasoline so that adding acetone to gasoline, or pure acetone, would cause internal combustion engine to malfunction. Also, seals, tubing, etc. would be damaged.
- 3 Efficiency drops more for values of the theoretical air-fuel less than 1 vs. greater than 1, and CO is produced in the former mode. Air pressure has little effect. Preheating the air, if possible at a cheap cost, helps some. Preheating the feed water also helps a bit. A high flue gas temperature results in a much more substantial loss in efficiency. A fuel that has a higher H to C ratio reduces efficiency for high H to C ratios. Fouled heat transfer surfaces reduce efficiency a bit.
- 4 The heat transfer is different because for a closed system $Q = \Delta U = \Delta H - p(\Delta V)$, and for an open system $Q = \Delta H$.
- 5 Oxygen, because the N₂ in the product of combustion with air uses up some of the available energy pool.
- 5 Combustion of H₂ in air gives a theoretical flame temperature of 4060°F but the actual temperature allowing for equilibrium is more like 3800°F. Preheating the fuel and air which might occur would raise both of these values.

Section 27.1

- 1 The magazine said that when water was poured into the funnel it would flow for up to 12 hours. When the author was asked about the apparatus, he admitted that the best he could do was have it run for a minute. The air in the spherical vessels was compressed when water was poured into the funnel; dissipation and friction caused the flow to stop.

Section 27.2

- 1 20 hp is much less than 68 kW, insufficient even at 100% efficiency.
- 2 Comparisons are heavily dependent on the assumptions one makes relating to the performance and capacity of the electric versus the internal combustion engine (ICE) vehicle. Since no current electrically powered vehicle matches the cruising speed, acceleration, and range characteristics of competitive gasoline-powered cars, this type of comparison is always clouded by whatever is assumed as the minimum acceptable performance for the electric. If the electric car must have the power/energy capability to drive repetitively 54 miles between battery charges, a considerably heavier electric

vehicle than 2800 lb is needed (more like 4000 lb is needed). A 50-mph road load power requirement is not a valid basis on which to size a power plant to propel highway vehicles.

Efficiencies are different from the table. Reasonable values are 36% thermal efficiency for the power generation facility, 91% electrical transmission efficiency, 10% refinery energy penalty charged to gasoline manufacturing, and 46% battery efficiency (assuming overnight recharge). The latter figure is considerably lower than the 70% figure in the table.

On this basis, the energy consumption for a currently feasible electric car used under city-suburban commuting conditions comes out to about 8300 Btu/mile versus 6000 Btu/mile for the Pinto-class gasoline powered car.

Section 27.3

1. The ball levitates because as the air reaches the expansion section of the funnel, it slows down to fill the larger cross section, and since the air is faster above the ball than below it, the pressure is higher below the ball than above it.
2. Figures b and c (which are not to scale). With tubes the equation to use is called Poiseuille's equation. With holes, the equation is called Torricelli's equation. With Poiseuille's equation, the velocity is proportional to the pressure head. Torricelli's equation states that the velocity is proportional to the square root of the pressure head, and indicates the maximum range for the liquid comes from a hole $\frac{1}{2}$ of the way up the cylinder whereas Poiseuille's equation designates a tube $\frac{1}{3}$ of the way up the cylinder.

Section 28.1

1. The heat of mixing of the compounds was exothermic and caused excess vapor to form and over-pressurize the storage tank.
2. Evolution of heat of mixing vaporized water, and drove some of the solution out of the tank.

Section 28.2

1. The accident is an example of the heat of mixing. The tank contained water condensate.
2. The concentrated NaOH and the weaker NaOH solutions mixed on breaking of the crust, releasing energy.

Section 29.1

1. Advertisers and even some heating engineers appear to overlook latent heat of vaporization. The evaporation of 10 gallons of water a day (modest for the humidification of most houses) requires more than 80,000 Btu equivalent to the consumption of about 80 cubic feet of natural gas per day. This is approximately 10 percent of the natural gas needed to heat a modest home on an average winter day. It makes no difference if humidification is

accomplished merely by placing pans of water on radiators. Unless condensation of water vapor releases energy to the house, it doesn't appear as if you could save energy overall by turning down the thermostat 4°F.

Section 29.3

1. Evaporative cooling is an excellent technology for low-cost cooling and works best in desert areas. In a swamp, the humidity is so high that little water evaporates, and, in addition, the humidity of the exit air is so high that conditions are uncomfortable for people.
2. (a) Salt build up in the circulating water; (b) scaling on the slats; (c) carry-out of salty vapor onto surrounding surfaces by the wind (drift)

Chapter 30

1. No. The solution method will have to be different than for continuous variables.
2. Variables associated with any other properties such as charge (changes have to be balanced), electrical and magnetic properties, etc.

Chapter 32

1. The equations for the time to drain each tank are:

Vertical cylinder

$$t = \frac{\pi D^2 \sqrt{h}}{\sqrt{8} C_d A_n \sqrt{g}}$$

Cone

$$t = \frac{\sqrt{2} \pi 15 n^2 \theta h^{3/2}}{5 C_d A_n \sqrt{g}}$$

Horizontal cylinder

$$t = \frac{\sqrt{8} L (D^{3/2} - (D-h)^{3/2})}{3 C_d A_n \sqrt{g}}$$

Sphere

$$t = \frac{\sqrt{2} \pi h^{3/2} (D - \sqrt{D^2 - h})}{3 C_d A_n \sqrt{g}}$$

where:

A_n = orifice area, ft²

g = 32.2 ft/s²

t = time to empty, s

C_d = 0.61 for sharp-edged orifice

= 0.80 for short, flush-mounted tube

= 0.98 for rounded orifice

Assume the orifice coefficient is constant. Pick an orifice area, D , θ , h , L , and C_d so that tanks are compatible (let h and D be the same). Then calculate t .

2. Refer to Problem No. 11 (p. 21) of the cited publication for the detailed information for instructors and the solution.